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ON THE TEMPERATURE, SECULAR COOLING AND
CONTRACTION OF THE EARTH, AND ON THE
THEORY OF EARTHQUAKES HELD BY
THE ANCIENTS

By T. J. J. SEE, A.M., L.Y.M., Sc. M. (MISSOU.), A.M., Ph.D. (BEROL.),
PROFESSOR OF MATHEMATICS, U. S. NAVY, IN CHARGE OF THE NAVAL
OBSERVATORY, MAKE ISLAND, CALIFORNIA



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BY T. J. J. SEE, A.M., LT.M., SC.M. (MISSOU.), A.M., PH.D. (BEROL.),
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OBSERVATORY, MARE ISLAND, CALIFORNIA.

(Read April 20, 1907.)

I. ON THE TEMPERATURE AND INTERNAL STATE OF THE EARTH.

§ I. *General Considerations.*

It is well known that Fourier devoted almost the whole of his life to those famous mathematical investigations by which he established the laws for the propagation of heat in solid bodies. His first memoir was communicated to the Institut de France in 1807, but with several subsequent memoirs was allowed to rest in the Archives till 1822, when all were at length published in the celebrated "*Théorie Analytique de la Chaleur*." Prior to this, however, in the *Bulletin des Sciences par la Société Philomathique de Paris*, avril, 1820, pp. 58-70, there appeared an "Extrait d'un Mémoire sur le Refroidissement séculaire du Globe Terrestre," which contains the earliest detailed statement of the secular cooling of the earth (cf. "*Oeuvres de Fourier*," edited by Darboux, Tome II., pp. 271-288).

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In 1827 Fourier submitted to the Academy of Sciences an additional memoir on the "Temperatures of the Terrestrial Globe and of the Planetary Spaces" (cf. "Oeuvres de Fourier," Tome II., p. 97). He justly remarks that the question of terrestrial temperature is one of the most important and one of the most difficult in the whole range of natural philosophy. This view is still held by physicists to-day, and therefore any inquiry which will materially advance our knowledge of the subject may be welcome to the investigator of the physical problems of our globe. Some of the results here obtained are only approximate; yet they appear to fix fairly accurate limits to the effects which may be ascribed to the movement of heat within the earth, and accordingly may not be wholly without interest to those who are occupied with this difficult subject.

The theory that our earth is undergoing secular cooling, and therefore contracting, is widely spread in the literature of contemporary science; in fact it is made the basis of nearly all current speculations in geology, geophysics, seismology and the related branches of natural philosophy. A theory so widely spread in modern thought and so long current would naturally have great presumptive evidence of truth, and therefore should not be lightly set aside. Yet it often happens that later researches supply criteria which were not available to the earlier investigators; and subsequent workers are required to take account of these advances. This appears to be the situation at the present time in respect to the doctrine of the secular cooling and contraction of the earth, which is currently adopted in so many of the physical sciences.

If it may be shown, when we determine the density, pressure and most probable distribution of temperature within the earth, that no circulation of convection currents has taken place since the globe attained approximately its present dimensions, that the effect of secular cooling is therefore sensible only in the crust, and that no deep-seated contraction has occurred since the earliest geological time, we shall be obliged to conclude that other causes should be found which are adequate to account for the phenomena heretofore explained by the effects of secular cooling. In particular it becomes advisable to subject the doctrine of contraction to a most searching examination and crucial test, in order to ascertain what justification

there is for the premises which have been so long adopted in geology and the related sciences. And to make the results of this criterion as convincing as possible, it becomes necessary to adopt mathematical methods, which inspire the greatest confidence in the final conclusions.

So long as contraction was the only available explanation of earthquakes and mountain formation, and no serious doubt had arisen as to the reality of the assigned cause, it seemed legitimate to adhere to the traditional theories of the physics of the globe. But since a different theory has been developed in the paper on "The Cause of Earthquakes, Mountain Formation and kindred phenomena connected with the Physics of the Earth," which explains the observed phenomena by the effects of water vapor accumulating beneath the earth's crust, and seems to be justified by the harmonious concordance of many facts not otherwise intelligible, it appears necessary to re-examine the foundations of the earlier reasoning.

It is true that the traditional theories were rejected in the paper on the cause of earthquakes, for reasons there assigned; but this step is a highly important one, and as the evidence may not be entirely convincing to others, it seems advisable to give a more connected view of the physical grounds on which the step was taken. The general grounds assigned in the former paper need not be repeated here; it is sufficient to recall that they were based partly on the principles of probability and partly on observed phenomena which appeared to admit of but one interpretation.

The paper on the cause of earthquakes grew out of certain phenomena observed during the great earthquake of San Francisco, and was a natural continuation of the previous work on the "Physical Constitution of the Heavenly Bodies" (cf. *A. N.*, 3992, 4053, 4104, 4152). As a result of these researches on the internal state of the heavenly bodies, the writer reached the conclusion that no convection currents exist within the earth, nor have such currents been possible at any time since the globe developed a density comparable to that which it has at present. It was therefore inferred that the cooling extends only through a very thin crust, and consequently the earth is not now appreciably contracting; nor has the contraction been sensible at any time since the terrestrial spheroid attained

approximately its present dimensions. This conclusion was essentially independent of the encrustation, and rested primarily on the resistance to the supposed convection movements caused by the pressure, which is so great as to make all the matter in the deeper portions of the globe behave as an aeolotropic elastic solid. The matter thus made effectively rigid by pressure, could cool only by conduction, and that process is so excessively slow and the heat transferred by it so small in amount as to render it of little effect in the postulated contraction of the earth.

In the former paper arguments were adduced to show that earthquakes and mountain formation depend principally on the secular leakage of the ocean bottoms, and not on the shrinkage of the globe. An attempt was made to justify this inference by an appeal to the observed lay of the mountains parallel to the sea coasts, and the recognized connection between volcanoes, earthquakes and mountain formation. Mention was also made of the inadequacy of the contraction theory to account for the height of mountains, and their congested distribution; and of various other considerations, such as the observed elevation of the sea coasts by earthquakes and the sinking of the adjacent sea bottom shown by the accompanying seismic sea waves. We shall now examine more at length the physical questions connected with the temperature of the earth, and this will afford a basis for judging of the validity of current theories, as well as of certain conclusions respecting seismological problems reached in the former paper.

§ 2. *The Probable Law of Temperature within the Earth.*

The exact process by which the matter of the earth was gathered together and formed into the spheroid which we now inhabit is quite unknown, and one can conceive of what probably took place only by means of dynamical principles applied to ideal conditions offering by analogy a greater or less degree of probability. In this way well guided imaginative conceptions may enable us to approximate the former physical conditions of our planet. For example, it is not likely that the earth as we now find it was formed very suddenly, all the material being brought together so rapidly that but little of the heat of condensation escaped into space. Neither is it probable that the process of agglomeration was so excessively slow that nearly

all the heat of condensation escaped from the surface by radiation through the atmosphere, thus leaving the slowly-accumulated nucleus within at low temperature. In fact this last view seems to be effectively contradicted by the observed internal heat of the globe; and if heat was retained in the layers just beneath the crust, it must likewise have been accumulated throughout the whole nucleus.

It is much more likely that the agglomeration went on with moderate rapidity, so that the primitive globe in formation cooled about as rapidly as a condensing mass of monatomic gas would do under like conditions. Such a gaseous globe retains a little over one half of the heat of condensation. There are many indications that the sun is such a gaseous globe, and the constitution of Jupiter and Saturn probably is more or less similar. It seems likely that in the formation of the earth the meteorites and finer planetary dust came together at such a rate that the whole new planet thus constituted was made to glow with maximum temperature at the centre, as in the case of a sphere of monatomic gas in a state of equilibrium under its own gravitation. Then as the planet grew in mass by the addition of other meteoritic materials, the pressure augmented also, and eventually became so great as to prevent circulation of convection currents. At length the surface gradually cooled by radiation, grew dense and solid, and thus finally arose the encrusted earth.

It must be remembered that until the earth attained a mass of considerable magnitude, the matter falling into it would not be heated to a very high temperature; for in the early stages of the planet the central temperatures would not be high, nor would the force of gravity be intense enough to condense greatly the central nucleus. But as the mass gradually grew in size, the force of gravity would naturally augment, and the temperature rise accordingly. The rise of temperature would take place throughout the central mass by the condensation of the nucleus under increasing pressure; and the deeper down the matter which condensed, the less of the resulting heat would escape to the surface. Thus when the impacts became more and more violent, under increasing gravity, and the surface temperature was much augmented, the central temperature would rise in nearly the same proportion; so that the central temperature would always be the maximum. Yet it is clear that as

we approach the surface the fall of temperature would be slow in all the inner shells of the nucleus. In fact a considerable sphere at the centre would have nearly uniform temperature. But the central temperature could not be lower than that of the enclosing shells; for, if so, the heat would flow towards the centre, and when uniformity was established throughout the nucleus, the flow would start again towards the surface, still leaving the nucleus the hottest part of the sphere.

If some such process be the way in which our globe condensed, it will follow that the temperature is nearly uniform in a central nucleus of considerable size; but towards the surface the fall of temperature would become much more rapid. The curve of temperature thus inferred for the epoch of consolidation corresponds closely to that of an ellipse, in which the semi-axis major represents the radius of the earth, and the semi-axis minor the temperature at the centre. We cannot, to be sure, feel entirely confident that this is the *exact* distribution of temperature within the earth; but it is quite clear that the curve is of this general form, and no doubt an elliptical distribution of temperature will give a close approximation to the truth, which probably is all we can hope for at present. Thus we have established one approximate criterion for the internal distribution of the terrestrial temperature.

The other important criterion is quantitative in character, and is to the effect that one half of the primordial heat of condensation still remains stored up in the globe. This is shown by the following general formula:

$$\frac{Q}{W} = \frac{k - \epsilon}{k - 1}, \quad (1)$$

where Q is the quantity of heat radiated away, W the total amount of work done by gravity, k the ratio of the specific heat of a gas under constant pressure to that under constant volume, and ϵ is the exponent $4/3$, in the adiabatic formula $p v^{\frac{4}{3}} = C$ (cf. *A. N.*, 4053, or Ritter's "Anwendungen der Mechanischen Wärmetheorie auf Kosmologische Probleme," Leipzig, 1882).

The temperature attained in the development of the earth must have been very great for all the inner portions, and hence we need not hesitate to adopt the monatomic theory as being most nearly

applicable to these extreme conditions. Accordingly, with $k = 1 \frac{2}{3}$, we have $Q/W = 1/2$; and we see that only one half of the heat of condensation has been radiated away, and an equal amount remains stored up in the condensing mass. We must then draw the temperature curve so as to fulfill these two conditions: an elliptical distribution, constructed on an absolute scale such that one half of the primordial heat of condensation is still stored up in the earth.

If it be urged that the earth's matter was not sufficiently heated to be monatomic throughout its whole history, we may recall that when $k = 1.4$, as in common air and most gases, the amount of heat stored up is about 81 per cent. (cf. *A. N.*, 4053); but as this biatomic phase would be of short duration, the extra accumulation during early stages would perhaps about compensate for the loss since surface cooling began. Accordingly a secular accumulation of one half of the primordial heat of condensation would seem to be nearly correct.

In his "Auwendungen der Mechanischen Wärmetheorie auf Kosmologische Probleme" ("Baumgärtner's Buchhandlung," Leipzig, 1882), A. Ritter has established the following formula for the condensation of a gaseous sphere:

$$c_p(\Theta_0 - \Theta_1) = A\eta r \quad (2)$$

where c_p is the specific heat under constant pressure, 0.2375, $\Theta_1 = 273^\circ$, $A = 1/424$, $r = 6,370,000$ meters, and

$$\eta = \int_0^r \left(\frac{g'}{g} \right) d\rho,$$

g being the acceleration of gravity at the surface and g' that at any depth where the radius is ρ . For uniform density

$$\frac{g'}{g} = \frac{\rho}{r},$$

and we have

$$\int_0^r \left(\frac{g'}{g} \right) d\rho = \frac{1}{r} \int_0^r \rho d\rho = \frac{r}{2}, \quad \text{so that} \quad \eta = \frac{1}{2}. \quad (3)$$

By means, however, of a more exact investigation, based on Laplace's law of density, Helmert calculated for Ritter the value $\eta = 0.73$, which is no doubt sufficiently near the truth. Accordingly with these values the above equation (2) gives

$$\Theta_0 = 46,455^\circ \text{ C.} = 83,619^\circ \text{ Fahr.} \quad (4)$$

Beginning at the centre with a temperature of $83,600^\circ \text{ Fahr.}$, we find for the elliptical distribution of temperature within the earth the values shown in the following table. It is found by calculation that this arrangement of the temperature fulfills the two conditions above specified, namely the elliptical distribution, and the following quantitative criterion:

$$\begin{aligned} & \pi(r_i^3 - r_{i-1}^3)\sigma_i\zeta_i^{-1}\Theta_i + \pi(r_{i-1}^3 - r_{i-2}^3)\sigma_{i-1}\zeta_{i-1}^{-1}\Theta_{i-1} + \dots \\ & = \pi \sum_{i=1}^{i=n} \left[\left(\frac{r_i}{a} \right)^3 - \left(\frac{r_{i-1}}{a} \right)^3 \right] \sigma_i \zeta_i^{-1} \Theta_i = 45,000(5.5)\pi. \end{aligned} \quad (5)$$

In the second member of this equation the average specific heat of the earth's matter is taken to be 0.2, and the same numerical value is used in evaluating the first member of the expression under the summation sign.

Radius.	Density Water = 1.0.	Pressure in Atmospheres.	Theoretical Rigidity Due to Pressure, that of Nickel Steel = 1.0.	Temperature.
1.0	2.55	1	0.0000	0.0°
0.9	3.75	198,760	0.198760	33500
0.8	4.99	483,691	0.483691	49000
0.7	6.21	842,921	0.842921	59200
0.6	7.38	1,260,966	1.260966	66600
0.5	8.46	1,710,730	1.710730	72500
0.4	9.40	2,152,114	2.152114	77000
0.3	10.12	2,521,620	2.521620	80000
0.2	10.74	2,861,507	2.861507	82500
0.1	11.07	3,050,870	3.050870	83500
0.0	11.21	3,135,727	3.135727	83600

§ 3. *The Laws of Density, Pressure and Theoretical Rigidity Within the Earth.*

Laplace's celebrated law of density for the earth results from an hypothesis introduced into Clairault's general differential equation for the equilibrium of a heterogeneous mass of fluid endowed with a rotatory motion, which permits the integration of the equation in some particular cases, and thus enables the geometer to connect the oblateness of the successive layers of the fluid with the radius of the spheroid, of which the density is supposed to be a function. In default of knowledge Laplace assumed as an hypothesis that the

law of compressibility of the matter, of which before its consolidation the earth consisted, was that the increase of the square of the density is proportional to the increase of the pressure, or $dp = \kappa \rho d\sigma$, the integrating of which gives (cf. *A. N.*, 3992)

$$\sigma = \frac{Q \sin(qx)}{x} = \frac{\sigma_0 \sin(qx)}{qx}. \quad (6)$$

When calculated numerically the density, pressure and theoretical effective rigidity are found to be as given in the foregoing table (cf. *A. N.*, 3992, 4104).

The hypothesis employed in deducing the rigidity of the earth and other heavenly bodies, namely that the rigidity is proportional to the pressure, has been discussed in *A. N.*, 4152, as follows:

"In ordinary solids such as the metals the property of rigidity is produced by the action of molecular forces which resist deformation. On the other hand the matter within a planet like the earth is really gaseous but above the critical temperature, and therefore in confinement made to behave as an elastic solid wholly by virtue of pressure which brings the molecules within distances at which they again become effective in spite of the high temperature. Thus in cold solids the property of rigidity is due simply to molecular forces which prevent deformation, while for gaseous matter in confinement under such pressure that it acquires the property of an elastic solid, the property of effective rigidity is due wholly to the pressure. In the paper above cited I have therefore taken the rigidity to be directly proportional to the pressure, and ignored all other influences, such as temperature, because by hypothesis the density is assumed to follow Laplace's law, or the monatomic law, in the case of purely gaseous masses, and the temperature is supposed to be conformable to the laws of density.

"This hypothesis seems legitimate, and almost certainly as accurate as Laplace's law and the monatomic law, upon which the calculated pressures depend. Moreover the validity of the hypothesis that the rigidity is proportional to the pressure appears to be confirmed by the close agreement of the numerical values of the earth's rigidity found in this way with those found by the recognized empirical processes depending on the tides and the polar motion."

If this reasoning is justifiable, it becomes possible to calculate the rigidity of the matter at any depth within the earth, and we are enabled to conclude that the yielding of our globe under the influence of tidal forces to which it may be subjected is mainly superficial. The results of these calculations are illustrated by the curves drawn in the accompanying diagram, Fig. *F*.

Observations seem to prove that in transmitting earthquake waves

the globe behaves throughout as a solid; and it must be held therefore that the matter in confinement acts as an æolotropic elastic solid, though if released from pressure it would instantly expand as vapor, owing to the enormously high temperature.

In the paper on the "Cause of Earthquakes," however, it is shown that notwithstanding this general law for the globe as a whole, there is a thin layer just beneath the crust which in seismic disturbances behaves as a fluid; and the disastrous shaking of the earth is due mainly to the enforced movement of currents in this layer. Yet this substratum of fluid is under such great pressure beneath the confining crust that the compressed lava transmits earthquake waves almost as if the globe were solid from the surface to the centre. Thus even this viscous substratum, under the least pressure of any of the heated matter within the globe, is sufficiently rigid to transmit to us faithfully the waves of compression and distortion which have been communicated to it. It is held that the actual rigidity may be greater than that calculated from the pressure, but it can not be less. We are therefore safe in following the rule that the rigidity is everywhere proportional to the pressure, and this gives us a definite view of the condition of the matter in the different layers.

Mr. R. D. Oldham, F.R.S., has shown that, so far as the propagation of earthquake waves enables one to judge (*Quarterly Journal of the Geological Society*, August, 1906), the matter of the earth's interior is essentially homogeneous down to within 0.4 of the radius from the centre, where some change appears to take place. This probably indicates that the nucleus is a magma of all the elements, with the density and rigidity increasing towards the center, owing to the augmentation of pressure; but the cause of the discontinuity about 0.4 of the radius from the center is not yet understood.

On the whole the most remarkable feature of the earth's constitution is the great increase of pressure towards the center. This gives our encrusted planet enormous rigidity and effective strength, or tenacity, to withstand any disrupting force. The average pressure or theoretical rigidity of all the *layers* composing the earth's mass is (cf. *A. N.*, 4104):

$$P = \frac{3}{4\pi r^3} \int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx = \frac{3 \cdot 3(\sigma_0 g)^2 \cdot r \cdot 4\pi r^3}{4\pi r^3 \cdot 2(\sigma_1 g) q^4} \left\{ \int_0^x \frac{\sin^2(qx) x^2 dx}{x^2} - \sin^2 q \int_0^x x^2 dx \right\}; \text{ and when } x = 1,$$

$$P = \frac{9(\sigma_0 g)^2 r}{2(\sigma_1 g) q^4} \left\{ \frac{q - \sin q \cos q}{2q} - \frac{\sin^2 q}{3} \right\} = 748,843 \text{ atmospheres. (7)}$$

And the average rigidity of all the earth's *matter* is:

$$P' = \frac{3}{4\pi r^3} \int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx \cdot \sigma = \frac{9(\sigma_0 g)^2 r \sigma_0}{2(\sigma_1 g) q^5 \sigma_1} \left\{ \int_0^x \frac{\sin^2(qx)}{qx} \cdot q dx - \frac{\sin^2 q}{q^2} [\sin(qx) - qx \cos(qx)] \right\} = 1,028,702 \text{ atmospheres. (8)}$$

The rigidity of steel is generally taken to be 808,000 atmospheres, but that of nickel steel is at least 1,000,000. The true rigidity of the earth probably lies between the limits set above, and it seems certain that it exceeds that of common Bessemer steel.

In these calculations no account is taken of the increase of rigidity due to the earth's solid crust, the effect of which is known to be considerable; for even the viscous layers just beneath the crust remain quiescent except when set in motion by the dreadful paroxysms of an earthquake. So difficult is this motion to effect that the throes thereby arising may perceptibly disturb a whole continent, and become sensible to observation throughout the world.

Accordingly if the matter of the interior, in confinement under great pressure, behaves as an æolotropic elastic solid, with a rigidity depending on the pressure and therefore increasing with the depth, it naturally follows that no currents can circulate at great depths; and we see that it obviously is not true, as some geologists have imagined, that liquid lava is extruded from deep down in our globe. Neither is it permissible to suppose, as Professor Chamberlin has done (cf. "Geology," Vol. I., p. 630, and Vol. II., p. 120), that our present volcanoes had their start at a depth of some 1200 to 1500 miles.

It follows from the theory developed in the paper on the cause of earthquakes that the original roots of volcanoes were but little deeper than the explosive forces which give rise to world-shaking

earthquakes. Observations show that this depth seldom exceeds twenty miles. Not only is there no extrusion of lavas from great depths at present, but it may also be affirmed with equal certainty that there never has been any such deep-seated extrusion since the earliest geological ages, or even since the epoch when our earth had the maximum surface temperature, before the beginning of encrustation. We may in fact feel sure that no currents were stirring at any considerable depth even when the surface was wrapped in flaming fluid, long before encrustation and secular cooling had begun. All the steam and other free vapors once within the planet had already been expelled, and formed about it a dense atmosphere.

Even if the earth had two or three times its present volume, a calculation of the corresponding pressures throughout the mass shows that there would be very little convective movement possible at any considerable depth. It seems to be true therefore that convection has played a very small part in the arrangement of the internal matter of the globe; and one may infer that the denser elements could not settle towards the center, except in the outermost layers. And the most probable view of the matter of the interior is that it is a magma of all the elements, the increase of density towards the center being due to pressure, which is sufficient to cause complete interpenetrability of all substances, especially under the high temperatures there prevailing.

§ 4. *The Hypothesis of Deep Movements Within the Earth Contradicted by Historical and Geological Evidence.*

It is an observed fact, deduced from the study of world-shaking earthquakes, that movements of this character have never been known to originate at greater depth than thirty, or, at the very outside, forty miles. It follows therefore that earthquakes arise either in the crust or in the layer just beneath it. Now if deeper movements of the globe are in progress, some of them would in all probability have been felt within the historical period; for they would not be similar to ordinary world-shaking earthquakes, but would be of much more widespread character, the shock being of more nearly equal intensity throughout the world. No such world-wide disturbance is recorded in the history of the civilized nations, nor is anything transmitted to us by the traditions of barbarous tribes which

may not be explained by ordinary earthquakes. The preservation of the ruins of temples of the classic period alone assures us that no really deep-seated convulsion of the earth has occurred within the last 2,000 or 3,000 years. This general fact seems therefore decidedly adverse to the doctrine of deep-seated movements of the globe.

To be entirely confident, however, that such cataclysms may not occur at very long intervals, it is necessary to consider the indications furnished by the ruins wrought by geological time. The existence of a vast number of more or less unstable natural pinnacles, in the form of columns of weather- and water-worn rock, scattered abundantly in various parts of the earth, all of an age to be reckoned in hundreds of thousands or millions of years, assures us that nothing approaching a deep and powerful convulsion of our planet has taken place within something like a million years. One naturally concludes therefore that such supposed convulsions, which have always been popular in geology, do not really take place at all. The fact that the continents and islands show the preservation of successive species of fossils, arranged in moderately conformable beds, and the recognized proof that the great continents have never greatly changed their places since geological history began, may be said to supply decisive evidence that no deep-seated convulsions, such as Elie de Beaumont and others were accustomed to imagine, ever take place even at periods to be reckoned in millions of years.

All important changes observed in the earth's crust must therefore be ascribed to external agencies, and especially to earthquakes, which originate within forty miles of the surface, and seldom extend to a depth greater than fifteen or twenty miles. Accordingly we may dismiss for the present any further consideration of this problem; but we shall again resume it after we have examined the distribution of temperature and the secular movement of heat deep down in our globe, which will give another proof that the interior of the earth is now and always has been quiescent.

§ 5. *The Secular Propagation of Heat from the Nucleus into the Enclosing Shells would not Give Rise to the Contraction of an Encrusted Planet.*

It was formerly held that the earth was a liquid mass stirred by

convection currents, and thus before encrustation of nearly uniform temperature throughout. This hypothesis lies at the basis of Lord Kelvin's famous paper on the secular cooling of the earth. But in more recent times the conviction has grown that the temperature must have been a maximum at the center, and a minimum at the surface. This law of temperature distribution has been found to be true of all gaseous masses when subjected to strict mathematical inquiry (cf. *A. N.*, 4053, 4104); and it is natural to think that a similar law holds for planets even after they have become encrusted.

Lane first arrived at such views, from his researches on the theory of the sun, in 1869; and subsequent investigators agree that the density, pressure and temperature would be highest at the center (cf. *A. N.*, 4053, 4104). In the paper on the "Physical Constitution of the Heavenly Bodies" (*A. N.*, 4053) reasons are assigned for holding the view that all bodies of considerable size must become monatomic by dissociation of the more complex molecules into atoms at their maximum temperature; and curves are given for the density and temperature corresponding to this condition. It is also shown that after passing through the monatomic condition, encrustation finally results from restricted circulation and surface cooling, which causes great increase of the surface density. If this view be admissible, it will follow that the central temperature is not materially lowered by the cooling incident to the formation of the crust.

We shall therefore be justified in concluding that the monatomic distribution of temperature still holds true approximately in an encrusted planet. But we have already given reasons why the temperature curve, in the case of a body like the earth, which may possibly be of a meteoritic origin, has nearly the form of an ellipse. If we look at the curve for a monatomic distribution of temperature, given in the accompanying plate, right hand upper corner, and imagine that the surface density increases as encrustation advances and the heat flows outward, we shall see that the monatomic curve may easily pass into an ellipse such as was postulated for an encrusted planet. Assuming the earth to be encrusted, and the internal temperature in any section to follow the law of an ellipse changing with the time, the question naturally arises: What would be the changes produced by the steady flow of heat under the conditions assumed by Fourier?

Some prominent geologists believe that the outflow of heat from the nucleus would produce a deep-seated secular contraction such as they imagine might have caused the subsidence of the ocean basins (cf. Chamberlin and Salisbury's "Geology," Vol. I., pp. 563 and 567).

If the initial distribution of temperature in any plane section of the earth corresponds to the ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{a^2(1-e^2)} = 1, \quad (9)$$

the distribution after a sufficient interval τ may be taken to be

$$\frac{x^2}{a'^2} + \frac{y^2}{a'^2(1-e'^2)} = 1. \quad (10)$$

In other words the form and dimensions of the ellipse will change with the time. The two ellipses will intersect at four points, and if they be revolved about the common minor axis, these points of intersection generate circles of no change of temperature; the points are given by the condition

$$x^2 \left(\frac{1}{a'^2} - \frac{1}{a^2} \right) + y^2 \left(\frac{1}{a'^2(1-e'^2)} - \frac{1}{a^2(1-e^2)} \right) = 0. \quad (11)$$

Here x becomes identical with the radius of the circle about the

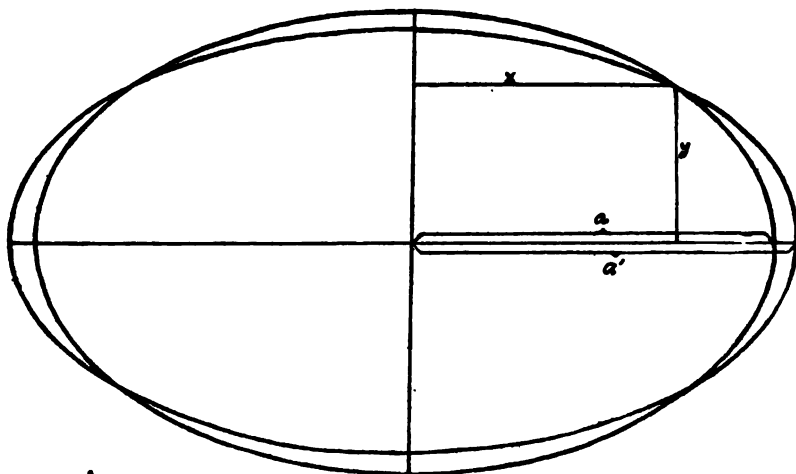


FIG. 1. Section of Ellipsoids.

y -axis, and may be calculated when a , a' , e and e' are known, by substituting the value of y in the original equation of the ellipse (9).

Now to show that no change of volume occurs by this propagation of heat from the center outwards, we may observe:

1. That although the major axis of the heat ellipsoid enlarges with the time, the minor axis diminishes, so that except for the slight loss at the surface the volume of the heat ellipsoid remains unchanged, and no heat escapes into outer space; hence there is a change of distribution but not in the total quantity of heat.

2. As this transfer takes place under the confinement of the crust and subjacent layers resting upon the nucleus, the change is necessarily made in such a way as not to do work upon bodies external to the thermodynamic system; nor is work done upon the thermodynamic system itself by external bodies. In either case the constancy of the amount of energy stored up would be altered, which is contrary to the hypothesis.

Any spherical shell $4\pi r^2 dr$, outside of the sphere of no change of temperature, already defined, would have another corresponding shell inside, in which the changes of volume would be equal but of opposite sign to that of the first. Therefore in general we should have

$$4\pi \sum_{i=-t}^{t=+t} r_i^2 dx_i \sigma_i \zeta_i^{-1} d\Theta_i = 0, \quad (12)$$

where $d\Theta_i$ is the change of temperature experienced by any shell, of density σ_i , and specific heat ζ_i . Hence denoting the variation of the elements of volume by δ , we should have, since the change of volume is directly proportional to the change of temperature,

$$\sum_{i=-t}^{t=+t} \delta(dV_i) = 0. \quad (13)$$

The conclusions thus briefly indicated may be stated otherwise as follows:

1. The inner shells of the nucleus, having lost heat, might shrink under the pressure to which they are subjected.

2. The outer shells of the nucleus, having gained heat, would have to expand, or the internal tension and latent heat would have to increase. This would be relieved either by bursting the crust, or

by molecular yielding towards the nucleus, which furnished the heat that caused the expansion.

3. Now to burst the crust would be doing external work. Also since the crust is very strong and its substratum deep, the movement of these superincumbent layers would be very difficult, and involve the expenditure of much energy. The easiest mode of adjusting the tension therefore would be by the molecular movement in the outer shells towards the inner shells of the nucleus, which have shrunk by loss of heat, and in such an adjustment the crust would not be disturbed.

4. No surface disturbances traceable to deep nuclear movements have occurred within the historical period, and geological evidence shows the fixity of the continents throughout all geological time. Therefore we may hold that earthquakes arising in the superficial layers are the only causes which have been active in shaping the topography of the surface since the moon was separated from the globe.

5. Since the effect of radial shrinkage in 100 million years is shown to be very small, different estimates ranging from 0.26 to 1.16 miles (cf. Chamberlin and Salisbury's "Geology," Vol. I., p. 573), it seems absolutely certain that progressive diffusion of heat deep down in the earth could produce no sensible effect at the surface.

Speaking of these effects of secular cooling, Chamberlin and Salisbury remark that "they are exceedingly small. Unless there is a very serious error in the estimated rate of thermal loss, or in the coefficients of expansion, cooling would seem to be a very inadequate cause for the shrinkage which the mountain foldings, overthrust faults, and other deformations imply. This inadequacy has been strongly urged by Fisher¹ and by Dutton.² In view of the apparent incompetency of external loss of heat, the possibilities of distortion from other causes invite consideration."

Thus the opinion here expressed is favorable to the views developed in the present investigation. Can it then be that the present negation of deep-seated movement since the earliest geological time is without significance in the argument against the theory of the

¹ "Physics of the Earth's Crust," Chap. VIII.

² *Penn. Monthly*, Philadelphia, May, 1876.

secular contraction of the globe? Does not the absence of such movement indicate that the effect of such cooling and contraction is wholly inappreciable?

It may be remarked also that the supposed sensible shrinkage is contrary to our hypothesis, based on what appear to be highly probable conditions, namely that no external work is done, but only an interchange effected between the central and peripheral parts of an essentially adiabatic system. On these several grounds therefore it is impossible to entertain the view that the shrinkage or movement of matter deep down in the earth ever exerts a sensible influence at the surface. The detachment of the main body of the matter composing the moon from the vast depression now occupied by the Pacific Ocean, with opposite tidal fragments from the Atlantic, is a much more probable view of the origin of the principal oceanic basins. The levels were no doubt much restored by the plasticity of the material and the subsequent action of the water and atmosphere, but earthquake forces on the other hand have largely counteracted this tendency to uniformity.¹

§ 6. *Why the Figure of the Earth can never Have Tended to the Tetrahedral Form.*

It is not without considerable surprise that thoughtful students of the physics of the earth have noticed in recent years the recurrence of the suggestion that the original form of the earth was that of a tetrahedron. It is difficult to understand what there is in this improbable conjecture to render it attractive to some minds. But such an hypothesis may no doubt be compared with Kepler's speculations on the regular solids, before the discovery of the true laws of the planetary motions. Kepler's hypothesis was set forth in the *Mysterium Cosmographicum*, 1596, and as given by Whewell in the "History of the Inductive Sciences," Vol. I., p. 416, is as follows:

"The orbit of the earth is a circle; round the sphere to which this circle belongs describe a dodecahedron; the sphere including this will give the orbit of Mars. Round Mars describe a tetrahedron; the circle including this

¹ Since this paper was completed I have received from Professor W. H. Pickering a copy of a suggestive paper, just published in the *Journal of Geology*, in which he deals with the origin of the moon. Many of his views are similar to those here adopted. The suggestion that the moon originated in the Pacific Ocean is due to Rev. O. Fisher, who published it in *Nature*, Jan., 1882, Vol. XXV, p. 243, and again in the second edition of the "Physics of the Earth's Crust," Chap. XXV.

will be the orbit of Jupiter. Describe a cube round Jupiter's orbit; the orbit including this will be the orbit of Saturn. Now inscribe in the earth's orbit an icosahedron; the circle inscribed in it will be the orbit of Venus. Inscribe an octahedron in the orbit of Venus; the circle inscribed in it will be Mercury's orbit. This is the reason of the number of the planets."

In this last line Kepler alludes to the five kinds of polyhedral bodies, known as the only "regular solids," corresponding to the five planets, besides the earth, which were then known.

When we consider these early views of Kepler in the light of the true laws of nature, nothing so much impresses us as the highly artificial character of the suggested cosmical system. But as the ancients had considered the heavens to be made up of spheres of crystal and glass, the contrast with actual nature implied in the system proposed was much less apparent in Kepler's time than in our own, because the heavens were then, through the influence of the Greeks, still viewed largely as a work of art.

The appearance in this late age of the doctrine of a terrestrial tetrahedron, however, is very remarkable. The earth has been known to be a spheroid differing but little from a sphere since 500 B. C., and the law of gravity by which Newton established the cause of the observed form of the globe has been universally recognized for over 220 years. As the earth has always been highly heated within, one can not doubt that the doctrine of fluidity as applied to it is valid. And the form of the surface ought not only to be spheroidal now, but also throughout the whole past history of our globe. This view is likewise confirmed by the figures of the other planets in space, which have been carefully investigated by astronomers ever since the invention of the telescope by Galileo in 1610.

Moreover Tresca's experiments showed that under great pressure all matter behaves as fluid. It is easily shown that a column of the stiffest granite or steel would not stand over five miles high, without crushing and vaporizing at the base. The column would begin to yield when the weight became sufficient to overcome the molecular forces of the material. A solid pyramid would resist crushing to much greater height than a shaft of uniform diameter, but the principle is the same; and no great height would be attained before even a pyramid of the hardest material would begin to spread at the base and flow, from its own weight. Thus there is a limit to the height

at which mountains would stand, but it seems not to be attained on our actual earth. We conclude therefore that even if the earth were as stiff as steel and given the tetrahedral form, the corners would be crushed down and the figure rapidly rounded up under its own attraction, and this deformation would also develop much internal heat. As the earth, assumed to be cold, could not maintain the tetrahedral form when once given it, it certainly would not tend to acquire it with all except a thin crust at high temperature and kept rigid only by pressure. The hypothesis of an original tetrahedral form for the earth must therefore be dismissed as not even a plausible delusion.

§ 7. *The Continental and Oceanic Features of the Terrestrial Spheroid Probably Depend on the Ruptures Produced when the Moon was Formed, and the Smaller Details of the Surface are due to Modifications of the Crust Made by Earthquake Forces Acting in the Underlying Substratum.*

If therefore on the one hand no movements originate deep down in the earth, and the effects of secular cooling at great depths have little or no influence in deforming the surface, while on the other it is shown that there never was a tendency for the earth's mass to assume the tetrahedral form, it follows that the details of the terrestrial spheroid must be explained by forces acting only in the layer just beneath the crust. To suppose that any tendency to a tetrahedral form can have modified the earth's surface is equivalent to the admission that the molecular forces are powerful, in shaping the crust, in comparison with the effects of gravity. Such a view, however, is known to be untenable, because under great pressure all bodies yield and flow like wax, as was found in Tresca's experiments on the hardest substances, to which allusion has already been made (cf. Tresca and St. Venant, "Sur l'écoulement des corps solides," *Mémoires des Savants Étranges*, Académie des Sciences de Paris, vols. 18 and 20).

The details of the lithosphere must therefore have been shaped by forces acting beneath the crust, and such depressions of level as originally resulted from the detachment of the moon from the earth. That the moon was originally derived from the rupture of the primitive earth-mass seems to be conclusively proved by Professor Sir G. H. Darwin's celebrated researches on this subject. We do not know at what stage the rupture occurred, nor how much larger in volume the

earth then was than it is now ; but the separation probably took place in the earlier history of our planet, before encrustation had begun.

The Rev. O. Fisher has calculated that a layer of matter of the density of granite (2.68) no more than 31 miles thick, taken from the outside of our globe, would furnish a mass equivalent to that of the moon. If the earth's radius was then larger than at present, the layer could be correspondingly thinner ; and it probably was sensibly larger then than it is now, though certainly not by so much as 25 per cent. As the rupture is supposed to have originated under the disturbing action of the solar tides, the tidally detached mass would not come from the entire hemispheres, but mainly from the tidal protuberances of the two sides, towards and from the sun. When the matter had been detached most of it was at length gathered together and formed into a satellite, but some considerable masses no doubt again fell back to the earth. It seems most likely that the oceanic depressions and continental platforms originated largely in the genesis of the moon. Part of the present distribution of these features on our globe is thus the work of pure chance, but others, as the Pacific, Indian and Atlantic oceans, probably represent the primitive sinks left by the original disruption. The inequalities remaining after certain masses had again united with the earth probably gave the foundations on which the continents and oceans have since been built. It is most unlikely that such a disruption could occur without leaving oceanic basins, and the Pacific and Indian oceans are evidently the area from which the matter of the moon was mainly derived. Instead of a uniform layer 30 or 35 miles deep, a hemispherical meniscus 50 or 100 miles deep at the center, and thinning out at the edges is naturally suggested.

Great modification and leveling of the inequalities of the basins would naturally be effected by the precipitation of some of the detached masses, and by the enormous bodily tides then at work upon the globe, which was no doubt still largely molten or but thinly encrusted. The long continuation of tidal action would largely smooth out the inequalities in the earth's surface, but it seems almost impossible that it could entirely remove the basins left by the detachment of the matter now forming the moon.

This, then, seems to be the most probable origin of the oceanic

basins, and continental platforms; and we probably are not justified in ascribing any sensible part of these inequalities of level to deep seated shrinkage of particular segments. For we have seen that the general shrinkage is quite incapable of producing such large effects, and there is still less reason why certain segments should shrink so much more than others. The average depth of 2.5 miles for the Pacific Ocean can not well be explained by shrinkage. It appears therefore that the great inequalities of the earth's surface resulted from the formative processes involved in the detachment of the moon, while the smaller inequalities such as mountains, high plateaus, and deep ocean troughs and abysses have been produced mainly by earthquakes acting in the layer just beneath the crust. In this way we may legitimately explain all the leading features of the earth's surface; but it is obvious that we cannot give the details involved in the formation of each continent and ocean, because there is no way of re-tracing this early history of our planet.

II. ON THE SECULAR COOLING OF THE EARTH.

§ 8. *Analytical Theory of the Propagation of Heat in Solid Bodies Applied to the Secular Cooling of the Terrestrial Globe.*

This subject was first treated with characteristic penetration by Fourier, in a memoir entitled "Le Refroidissement Seculaire du Globe Terrestre," communicated to the Philomathique Society of Paris in 1820 (cf. "Oeuvres de Fourier," Tome II, pp. 271-288). It had, however, already been touched upon in the "Théorie Analytique de la Chaleur" (chap. lx., § II., p. 427 et seq.), which, after a delay of some 15 years, was finally published in 1822.

Lord Kelvin's famous discussion of the "Secular Cooling of the Earth" (Appendix D, Thomson and Tait's "Nat. Phil.," Vol. I., Part II.) is based on Fourier's methods; but the constants were carefully determined from new experiments on underground temperature, which gave the conductivity of average rock, and thus made possible important estimates of the age of the earth. Rev. O. Fisher has also treated this and many other questions in his valuable and suggestive work on the "Physics of the Earth's Crust" (second edition).

The mathematical treatment consists in determining by Fourier's fundamental equations the actual temperature at any point in a solid

extending to infinity in all directions, on the supposition that at an assumed initial epoch the temperature had two different constant values on the two sides of a certain infinite plane; and in finding at the same time the rate of variation of temperature from point to point in the solid. To these ends Fourier has demonstrated the following familiar equation for the linear conduction of heat ("Oeuvres de Fourier," Tome II., p. 273).

$$\frac{d\Theta}{dt} = \kappa \frac{d^2\Theta}{dx^2}. \quad (14)$$

In this equation Θ denotes the temperature for the depth x , at the time t , so that x is the distance of any point from the middle plane, and κ is the conductivity of the solid rock composing the crust, measured in terms of the thermal capacity of the unity of bulk; that is, κ is equal to the number of units of heat which would pass across one square foot of a plate of rock one foot thick in a year, when the two faces of the rock are maintained at temperatures differing by 1° Fahr., the unit of heat being the amount required to raise one cubic foot of the rock through 1° Fahr. By careful experimental observations on several kinds of rock *in situ* Lord Kelvin found that $\kappa = 400$ (cf. "Théorie Analytique de la Chaleur," Chap. ix., § II.; and especially "Le Refroidissement Seculaire du Globe Terrestre," "Oeuvres de Fourier," Tome II., pp. 271-288; Thomson & Tait's "Nat. Phil.," Vol. I., Part II., Appendix D; Fisher's "Physics of the Earth's Crust," second edition, p. 67 et seq.).

If a, β, γ be any arbitrary constants whatever, and $f(a, \beta, \gamma)$ a function of these quantities, and x, y, z the coördinates of any point of the infinite solid, the general differential equation for the propagation of heat is

$$\frac{d\Theta}{dt} = \kappa \left(\frac{\partial^2 \Theta}{\partial x^2} + \frac{\partial^2 \Theta}{\partial y^2} + \frac{\partial^2 \Theta}{\partial z^2} \right). \quad (A)$$

And the general integral applicable to the most varied cases, subject to the appropriate surface conditions, indicated by the physical nature of the problem, is

$$\Theta = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} t^{-\frac{3}{2}} \cdot e^{-\frac{\{(a-x)^2 + (\beta-y)^2 + (\gamma-z)^2\}}{4t}} \cdot f(a, \beta, \gamma) da d\beta d\gamma. \quad (B)$$

When the diffusion of heat takes place in every direction the state of the solid is represented by the integral

$$\Theta = \frac{1}{2^3(\pi\kappa t)^{\frac{3}{2}}} \iiint e^{-\frac{\{(\alpha-a)^2 + (\beta-y)^2 + (\gamma-z)^2\}}{4\kappa t}} \cdot f(\alpha, \beta, \gamma) d\alpha d\beta d\gamma. \quad (C)$$

If the initial heat is contained in a determinate portion of the solid mass, one must take account of the limits which include this heated part, and the quantities α, β, γ , which vary under the integral sign, can not take values exceeding these limits (cf. "Théorie Analytique de la Chaleur," Chap. lx., p. 445). In the case of a symmetrical body like the terrestrial spheroid, it is usual to take the internal distribution of heat to be symmetrical about the center of gravity, which greatly simplifies the general problem. Observations made in many lands indicate that the isothermal surfaces are about equally near the surface at all places, except for the effects of unequal conductivity in the crust; and hence the symmetrical distribution of heat assumed to hold true within the globe seems to be justified. The probable mode of formation of the earth, and the long period during which it has existed, give other grounds for the hypothesis of a symmetrical distribution of the primordial heat about the center of gravity; the unequal temperatures near the surface, due to unequal conductivity in cooling, being confined to a shallow layer of very small extent compared to the globe as a whole. In treating of the heat flowing outward from the center of a symmetrical body like the earth, it thus becomes sufficient to consider the propagation of heat in a single direction normal to the surface. The triple integral is thus reduced to a single integral corresponding to the single variable coördinate, as in the differential equation (14).

The form given the equations by Lord Kelvin and Rev. O. Fisher is but slightly different from that originally used by Fourier, who was occupied with the subject for more than a quarter of a century; but as Lord Kelvin determined the constant of conduction with great accuracy, and also carefully investigated the observed average rate of the increase of temperature with the depth, we shall generally follow his notation, which will also facilitate the comparison of his results with those here obtained.

The rate of variation of the temperature per unit of length perpendicular to the isothermal plane is

$$\frac{d\Theta}{dx} = \frac{V}{\sqrt{\pi\kappa t}} e^{-\frac{x^2}{4\kappa t}}; \quad (15)$$

and the temperature at any point (x, t) in the solid is

$$\Theta = \Theta_0 + \frac{2V}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{\kappa t}}} e^{-s^2} ds. \quad (16)$$

In these equations V = half the difference of the two initial temperature and Θ_0 = their arithmetical mean.

It may easily be proved by differentiation that the expression for Θ satisfies Fourier's equation (14).

When $t=0$, the expression for Θ , x being positive, becomes

$$\Theta_0 + \frac{2V}{\sqrt{\pi}} \int_0^\infty e^{-s^2} ds = \Theta_0 + \frac{2V}{\sqrt{\pi}} \cdot \frac{1}{2} \sqrt{\pi} = \Theta_0 + V. \quad (17)$$

For all negative values of x , $\Theta = \Theta_0 - V$.

By differentiating (16) we obtain $\frac{d\Theta}{dx}$; and it is easy to see that for all values of t , the second term of the right member of this equation has equal positive and negative values for corresponding values of x . Taking Lord Kelvin's experimental value of the conductivity, $\kappa = 400$, equation (15) is reduced to the form

$$\frac{d\Theta}{dx} = \frac{1}{35 \cdot 4} \frac{V}{\sqrt{t}} e^{-\frac{x^2}{1600t}}. \quad (18)$$

Lord Kelvin remarks that if $t = 1,000$ million years, and $x > 3,000,000$ feet, the exponential factor becomes less than $e^{-4.6}$, or less than $1/270$, which may be neglected as insensible. This indicates that at depths greater than 568 miles the rate of variation of temperature does not become sensible in 1,000 million years. A temperature gradient thus exists only within a thin crust, and the influence of curvature of the surface may be neglected; so that the solution in the case of Fourier's infinite solid becomes immediately applicable to the cooling of the earth.

If we take $t = 100$ million years from the beginning of the radiation,

$$\frac{d\Theta}{dx} = \frac{1}{35 \cdot 4 \times 10^5} V e^{-\frac{x^2}{1600 \times 10^8}}. \quad (19)$$

By plating this equation Lord Kelvin found the curve for the rate of variation of temperature in the earth, 100 million years after the initial epoch, on the hypothesis that the surface temperature was suddenly lowered V degrees, and kept at this figure, so as to produce a steady flow of heat from within outward.

He took $V = 7000^\circ$ Fahr.

§9. *The Age of the Earth's Consolidation Calculated by the Fourier-Kelvin Method.*

Considering the earth to be a sphere of the same conductivity as average rock, we have for the rate of augmentation of temperature downward

$$\frac{d\Theta}{dx} = \frac{V}{\sqrt{\pi\kappa t}} e^{-\frac{x^2}{4\kappa t}} = \frac{1}{35.4} \frac{V}{\sqrt{t}} e^{-\frac{x^2}{16.0t}}, \quad (18)$$

κ being 400, when the units are the foot, year, and degree Fahrenheit. Solving this equation for t , and putting $V = 7000^\circ$ Fahr., we have

$$t = \left(\frac{51 V}{35.4} \right)^2 = 101,673,000 \text{ years.} \quad (20)$$

This is Lord Kelvin's method of estimating the age of the earth, or the duration since the beginning of the consolidation of the crust, which is supposed to have occurred very soon after the initial epoch.

We have already seen that the assumption of an original uniform temperature for the earth is only a first approximation to the true condition, not justified by a closer examination of the subject. The mathematical theory of the heat distribution in a gaseous globe shows that the temperature increases rapidly towards the center, and hence falls off correspondingly near the surface. Relatively to the average temperature of the whole mass, that of the surface is very low, and that of the center quite high. This is the condition in a gaseous sphere, and it seems certain that it cannot be greatly modified by the surface cooling which leads to encrustation. We have seen that this latter arises mainly from resisted circulation, and retarded supply of heat from the under layers, as the surface density increases. Prior to the beginning of surface cooling the planet passes through a stage of maximum temperature, and heat is both radiated and conducted through to the outer layers; but eventually the resistance to propagation of heat becomes so great that a fall of temperature is inevitable.

In the case of the earth there is excellent reason to conclude that the surface temperature never much exceeded 2000° Fahr.

The experiments of Professors Rücker and Roberts-Austen at the Royal College of Science, London, on basalt or dolerite of Rowley Regis, undertaken at the suggestion of the Rev. O. Fisher, showed that this rock was completely fused at 1688° Fahr. Basalt is a typical rock of the earth's crust, prevalent in nearly all volcanic districts; and it seems probable that a temperature of 2000° Fahr. would therefore not only fuse all the principal rocks of the earth's surface but also reduce many of them to a state of vapor.

The fact that the other planets of our solar system are not at present self-luminous, though the larger masses are known to have high internal temperature, tells against the theory of a very high surface temperature also in the case of the earth. For although we view the other planets at only one stage of their existence, and therefore cannot fully judge of their conditions at other cosmical epochs, yet the absence of self-luminosity when so much heat is known to be stored up within these planets can only indicate that a great lowering of temperature always takes place near the surface, as is also true in a sphere of monatomic gas. Thus it is not probable that even at the maximum the surface temperature of such masses would be very high. There are clear indications that Lord Kelvin's estimate of 7000° Fahr. is much too great; and in all probability we shall not be far wrong in using 2000° as the most acceptable value in all calculations on the secular cooling of the terrestrial globe. The temperature will increase with the depth, but for a shallow layer we may take it to be uniform; the temperature of 2000° then would not correspond exactly to the surface, but rather to the average of a thin sheet forming the boundary of the molten mass. As the outer layer was no doubt agitated from beneath, it would both lack in uniformity of temperature, and also be constantly changing, so that a mean temperature of 2000° Fahr. seems to be the closest approximation we can make to the true conditions.

Using $V = 4000^{\circ}$ in formula (20), we get $t = 33,208,850$ years; which is the age of the earth on this hypothesis. When $V = 2500^{\circ}$ Fahr., we find $t = 12,972,200$ years. And if $V = 2000^{\circ}$ Fahr., the result is $t = 8,302,210$ years, a comparatively short duration. As the



melting temperature of basalt is less than 1688° Fahr., the smaller value for V obviously is to be preferred. Thus the assumed surface temperature of 2000° Fahr. seems sufficiently high, and our most probable age of the earth calculated in this way is

$$t = \left(\frac{51 V}{35 \cdot 4} \right)^2 = 8,302,210 \text{ years.} \quad (21)$$

Accordingly, we conclude from this Fourier-Kelvin formula that the age of our encrusted planet can scarcely exceed 10 million years, which accords very well with the duration inferred from the theory of the sun's heat (cf. *A.N.*, 4053).

§ 10. *The Age of the Earth's Consolidation Calculated by Fisher's Method.*

The Rev. O. Fisher has developed another method for calculating the age of the earth which we shall now explain. It is in the main independent of Lord Kelvin's procedure based on Fourier's equation for the rate of increase of temperature downward, and has some advantages over it. Fisher's method is treated in Chapter vi., and also in the Appendix, to the second edition of his "Physics of the Earth's Crust." He established the following formulæ:

$$\left. \begin{aligned} V &= 2\mu e^{\mu^2} M \cdot \lambda \left(1 + \frac{\gamma}{k} \right) \\ &= 2\mu e^{\mu^2} M \lambda, \end{aligned} \right\} \text{for inert substratum, in which } \gamma = 0. \quad (22)$$

$$\beta = \frac{V}{M} \frac{1}{\sqrt{4\kappa t}}, \quad (23)$$

$$k = \mu \sqrt{4\kappa t}, \quad (24)$$

$$M = \int_0^{\infty} e^{-z^2} dz.$$

In these equations μ is a function differing but little from unity; M is the definite integral $\int_0^{\infty} e^{-z^2} dz$; κ the coefficient of conductivity taken to be 400, as in Lord Kelvin's work; k is the thickness of the earth's crust; β the surface rate of augmentation of temperature downward; λ is the latent heat of molten rock measured in terms of the amount of heat required to raise one cubic foot of the rock

through 1° Fahr.; and Λ is the latent heat measured in thermal units centigrade, water being the standard substance. In the appendix, p. 20, Fisher shows that Rücker's experiments make $\Lambda = 49.60$, the corresponding value for water at zero centigrade being 79.25. Taking the mean specific heat of average rock at 0.22, he makes $\lambda = 406^{\circ}$ Fahr., and $V = 1688^{\circ}$ Fahr. This is the temperature at which basalt is entirely melted. Finally, the quantity y is a function representing the activity of the substratum, and therefore zero when the layer is inert (cf. Chapter vi., p. 73).

Using these values Fisher finds for an inert substratum, that the true values are:

$\mu = 1.007$; $M = 0.7493736$; and the thickness of the crust

$$k = \frac{51 \times 1688 \times 1.007}{5280 \times 0.74937} = 21.91 \text{ miles.} \quad (25)$$

He concludes that the least thickness of the crust will be $\frac{V}{\beta} = 16.30$ miles, and that the true thickness of the crust will lie between 16.30 and 21.91 miles. If we take $k = 17.5$ miles, which is very near the thickness of the crust indicated by the great earthquake which devastated San Francisco, and apply formula (24) we find for the age of the earth

$$t = \frac{k^2(5280)^2}{\mu^2 4\kappa} = 5,262,170 \text{ years.}$$

Using $k = 21.91$ miles, in the same formula, Fisher finds

$$t = 8,248,380 \text{ years.} \quad (26)$$

This age for the encrustation of the earth seemed to him surprisingly small, and he therefore remarked:

"This is a far shorter period than geological phenomena appear to require, for although it is not possible for them to assign any definite limit to the world's age, we can form some idea of an inferior limit which it must have exceeded. Sir A. Geikie thinks that the stratified rocks alone, which contain organic remains, can not have taken much less than 100 million years for their formation."

The Rev. O. Fisher then proceeds to examine the hypothesis of an energetic substratum, and by this process reaches a greater age for the world. But for reasons pointed out in the previous paper on the cause of earthquakes, the hypothesis of an inert substratum is

obviously the proper one. For the substratum is shown to move only under the throes of an earthquake, and no circulatory movement of lava exists even just beneath the crust. Hence we adhere to the result there obtained, and must consider the significance of the small age of the earth. It will be seen that for a thickness of 22 miles, the age of the earth's consolidation is almost exactly the same as that reached by the use of Lord Kelvin's formula.

§ 11. *Remarkable Agreement of the Times Since the Consolidation of the Globe as Concluded from these Two Methods.*

The result found by Lord Kelvin's method rests upon the observed rate of increase of temperature downward, namely 1° Fahr. for 51 feet, which is about the same as the value used by Fourier nearly a century ago, and not improved upon by the deep borings made in recent years. It also rests upon the assumed surface temperature of 2000° Fahr., which probably is comparatively near the truth. Is it purely an accidental coincidence that with these data one is led by the Fourier-Kelvin formula to an age of 8,302,210 years, while by Fisher's formula, depending on the thickness of the crust essentially verified by earthquake phenomena, one finds the almost identical age of 8,248,380 years? Moderate variations of the data might derange this excellent agreement somewhat, but probably no change of the constants within admissible limits would produce extreme discordance in the resulting ages of the earth. It seems therefore difficult to escape the conclusion that these figures really approximate the true age of our encrusted planet. At least the period since the consolidation is of the order of ten million years.

Different investigators will naturally form different estimates of the age of the earth as found by the several methods of approximation; but it is difficult to see how the larger values formerly current can be justified by physical research based on the propagation of heat involved in the secular cooling of the globe. The writer has not the geological learning requisite for the use of the methods based on sedimentary rocks and their deposits of organic remains, but it seems very doubtful if these methods can lay claim to even approximate accuracy; and to most minds the conclusions drawn from the physical methods will naturally carry much greater weight.

Some considerations, however, based on the probable average

rate of the elevation of the Andes, taken at only one tenth of an inch a year, or ten inches in a century, seem to show that the age of these mighty mountains need not much exceed three million years. In the case of the mountains west of the Rockies a numerical estimate is not quite so easy, but it is doubtful if anything authorizes an estimate exceeding five million years. In this immense period the whole country west of Laramie may have been raised from the sea; in fact this is indicated by the abundant fossils of Saurians in the beds of Wyoming, as well as by the numerous parallel ranges of mountains in Nevada and California, showing the successive recessions of the sea. One is led therefore to think that after all our consolidated globe may not have an age exceeding eight or ten million years. In comparison with the brevity of human history such periods are almost infinite; and so little is known of the rates of variation of organic species under the unknown conditions of the past, that we may well hesitate before assuming longer periods for the life of our encrusted planet.

In contemplating this result we are again confronted with the question of the cosmical significance of radium. Several years ago when the enthusiasm over the radium discoveries was at its height there were those who admitted a terrestrial history of a thousand million years (cf. Professor Sir G. H. Darwin's presidential address to the British Association at Capetown, 1905). But mysterious as radium still remains, it is doubtful if such a view is generally held to-day. It is a remarkable fact that the more we study radium, the less we seem to really understand the part it plays in cosmical processes. So far at least there is no proof that it exerts any sensible influence, except possibly in chemical transformations.

§ 12. *Some of the Results of the Researches on Radium.*

In spite of the great labor bestowed upon the study of radium by many devoted and enthusiastic investigators, it can hardly be said that we have up to this time any conclusive results as to the cosmical significance of this very wonderful element. The theories of radium disintegration are well known, but not universally accepted. Lord Kelvin is one of those who still ascribe the Sun's heat to the potential energy of the mutual gravitation of its own matter; and he denies that radium plays any appreciable part in solar activity.

Major Dutton tried to explain the activity of volcanoes by means of periodic outbursts produced by radium, but the distribution of these vents along the shores of continents, on islands and in the sea, while none at all break out in the interior of continents, shows that there is a dependence on the oceans, and proves that radium cannot be the active cause in producing eruptions. For the experiments of the Hon. R. J. Strutt have proved that radium is widely distributed in the rocks of the earth's crust, such as granite; but he found on the other hand, that some basalts show scarcely a trace of it. This does not speak favorably for the view that radium is the cause of the earth's internal heat and volcanic outbreaks. For if radium were the cause basalts ought to be rich in the element which had caused the expulsion of this rock from volcanoes; and since all granite contains abundant radium, volcanoes ought to break out in the interior of continents, such as Africa, Australia, North and South America, Europe and Asia; but this is contrary to observation. It is not possible therefore to entertain the view that radium has any sensible connection with volcanic activity.

Of late even the terrestrial origin of radium has seemed doubtful, and in *Nature* of February 1, 1907, Professor J. Jolly, of Dublin, has suggested several considerations indicating that radium may come to us from the sun, in the form of infinitesimal corpuscles, expelled principally by the pressure of the sun's light. So far as we can now see this extra-terrestrial source of radium is by no means improbable. But whether this suggestion be verified by time and experience or not, it seems certain that radium in the earth's crust is essentially dormant; at least it plays little part in the physics of planets such as the earth, except perhaps in chemical transformations.

It probably is not without significance that in order to make the theory harmonize with the observed temperature gradient, Strutt attributes radium only to the crust, and not to the interior matter of the earth. If radium comes from the sun, it would lodge in the oceans, and be carried down into the sedimentary and other rocks, as now observed. In the absence of decisive proof we must suspend judgment, but at present one can only say that there is no evidence that radium is an important agency in cosmical processes witnessed upon our globe. For the sake of comparison, however, we give

Strutt's curve of temperature calculated on the hypothesis that radium in the earth's crust is the principal cause of the observed internal heat of the globe. (*Proc. Roy. Soc.*, Vol. 77, 1906.)

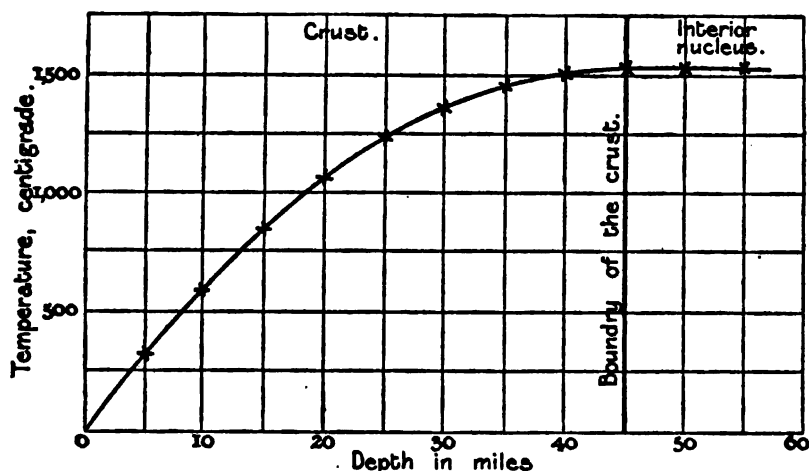


FIG. 2.

III. ON THE AGE OF THE CONSOLIDATION OF THE GLOBE AND ON THE SECOND APPROXIMATION TO THE LAW OF TEMPERATURE NEAR THE SURFACE.

§ 13. *Consideration of the Twelve Fourier Solutions.*

The methods here employed are those of Fourier, with the constants determined by Lord Kelvin. In view of the great uncertainty heretofore prevailing respecting the age of the earth's consolidation, we have thought it advisable to consider in all twelve cases, namely, three distinct times, of 10, 100, and 1000 million years each, and four initial temperatures of 2000°, 4000°, 8000° and 12,000° Fahr. respectively. These twelve solutions are illustrated by the diagrams in the accompanying plate. If the earth had been of uniform temperature throughout, no doubt its actual history would be essentially included in one of the accompanying diagrams.

But we have already seen reasons for holding that the central temperature was very high, and the surface temperature quite low; and moreover there is no doubt that the secular cooling is confined almost entirely to the crust. In considering the age of our earth

therefore we may pass over the diagrams which are based on very high initial temperature. In like manner we may reject those diagrams which are based on such long periods as 1000 million years. For the same reasons a period of 100 million years is much too long. It seems certain that the time since the consolidation of the globe is of the order of 10 million years; and that the surface temperature at the initial epoch did not much exceed 2000° Fahr., and it may never have quite equaled this figure.

But as the actual temperature rises downward, not only in virtue of the surface cooling, but also in accordance with the initial distribution of temperature throughout the globe as a whole, before cooling began, we have to consider the effects of a uniform temperature of say 2000° , and of an independent temperature gradient increasing with the depth. The loss of heat now going on is similar to that depending on the gradient alone—small in amount and very uniform in its rate. Each separate part of this double flow implies rise of temperature downward, and thus we may be sure that the true curve of temperature is steeper than those calculated on the hypothesis of uniform temperature. Thus the rate of augmentation of temperature downward also becomes greater than that calculated in the diagram. The effect then of the original independent gradient is to considerably raise the Fourier temperatures at any depth, and to maintain also a larger rate of augmentation of temperature than the calculated rate.

§ 14. *Approximation to the Actual Law of Temperature near the Surface.*

If we take the Fourier gradient established by secular cooling after 10 million years as giving the original rise of temperature within the earth, before cooling began, which in any case can differ but little from the truth, we may calculate the actual distribution of temperature within the earth's crust as follows:

1. Having computed the rate of augmentation of temperature, and by integration, found the curve of temperature itself for a surface temperature of 2000° and a duration of 10 million years, we calculate likewise the same curves for a duration of 20 million years.
2. The difference between these two sets of curves, one for $t=20$ million, the other for $t=10$ million years, when carefully

tabulated, and added algebraically to the ordinates of the original Fourier solution, in which the uniform temperature was 2000° , and $t = 10$ million years, gives very nearly the true curve for the temperature near the surface. This is illustrated by Fig. *D*, in the diagram. The formulæ used are:

For the rate of augmentation of temperature

$$\frac{d\Theta}{dx} = \frac{1}{35.4} \frac{V}{\sqrt{t}} e^{-\frac{x^2}{1600t}}, \quad \frac{d\Theta'}{dx} = \frac{1}{35.4} \frac{V'}{\sqrt{t+\tau}} e^{-\frac{x^2}{1600(t+\tau)}}, \quad (27)$$

where both t and τ are taken to be each 10 million years, and $V = V'$. For the curve of temperature we have

$$\left. \begin{aligned} \Theta &= \frac{1}{a} \int_0^{\infty} \frac{d\Theta}{dx} dx \\ \Theta' &= \frac{1}{a} \int_0^{\infty} \frac{d\Theta'}{dx} dx \end{aligned} \right\} \quad (28)$$

$$\Theta_1 = \frac{1}{a} \int_0^{\infty} \frac{d\Theta}{dx} dx + \frac{1}{a} \left\{ \int_0^{\infty} \frac{d\Theta}{dx} dx - \int_0^{\infty} \frac{d\Theta'}{dx} dx \right\} = \Theta + (\Theta - \Theta'), \quad (29)$$

in which $a = 2\sqrt{kt}$ (cf. Appendix *D*, Thomson & Tait's "Nat. Phil.," Vol. I., part II., p. 477).

More generally the formulæ become

$$\left. \begin{aligned} \frac{d\Theta}{dx} &= \frac{1}{35.4} \frac{V}{\sqrt{t}} e^{-\frac{x^2}{1600t}}, \\ \frac{d\Theta'}{dx} &= \frac{1}{35.4} \frac{V'}{\sqrt{t+\tau_1}} e^{-\frac{x^2}{1600(t+\tau_1)}}, \\ \frac{d\Theta''}{dx} &= \frac{1}{35.4} \frac{V''}{\sqrt{t+\tau_1+\tau_2}} e^{-\frac{x^2}{1600(t+\tau_1+\tau_2)}}, \\ &\vdots \\ \frac{d\Theta^i}{dx} &= \frac{1}{35.4} \frac{V^i}{\sqrt{t+\tau_1+\tau_2+\dots+\tau_i}} e^{-\frac{x^2}{1600(t+\tau_1+\tau_2+\dots+\tau_i)}}. \end{aligned} \right\} \quad (30)$$

Or when the times are reckoned from arbitrary epochs

$$\frac{d\Theta^i}{dx} = \frac{1}{35.4} \frac{V^i \cdot e^{-\frac{x^2}{1600\{t+(\tau_1-t_1)+(\tau_2-t_2)+\dots+(\tau_i-t_i)\}}}}{\sqrt{t+(\tau_1-t_1)+(\tau_2-t_2)+\dots+(\tau_i-t_i)}}.$$

And

$$\Theta_i = \frac{1}{a} \int_0^x \frac{d\Theta}{dx} dx + \frac{1}{a} \left\{ \int_0^x \frac{d\Theta}{dx} dx - \int_0^x \frac{d\Theta'}{dx} dx \right\} + \frac{1}{a} \left\{ \int_0^x \frac{d\Theta'}{dx} dx - \int_0^x \frac{d\Theta''}{dx} dx \right\} + \cdots + \frac{1}{a} \left\{ \int_0^x \frac{d\Theta^{i-1}}{dx} dx - \int_0^x \frac{d\Theta^i}{dx} dx \right\}. \quad (31)$$

Finally

$$\Theta_i = \Theta + (\Theta_1 - \Theta'_1) + (\Theta'_1 - \Theta'_2) + (\Theta'_2 - \Theta'_3) + \cdots + (\Theta^{i-1}_i - \Theta^i_i). \quad (32)$$

the subscripts on the right corresponding to the i arbitrary epochs.

In the application of these equations we must remember that this multiple process is valid only for values of x smaller than that corresponding to the maximum of Θ_i . For in Fig. *D*, we see that there is a maximum to the multiple temperature curve, and the true course of it can not be determined beyond this point. The apparent fall of temperature at greater depths indicates the failure of the process. But by taking suitable periods of time, and appropriate values for $V, V', V'', \dots V^i$, one may approximate the true curve asymptotically near the surface, and carry the determination to any desired depth.

In our present numerical work we have thought it sufficient to take $\tau_1 = 10$ million years, and $V' = V = 2000^\circ$. By carrying this process far enough we may obtain a multiple solution which is almost absolutely rigorous, and it will include all the effects of rising temperature beneath the surface as well as the uniform temperature embraced in the original solution of Fourier. The principal difficulty in extending the method to the propagation of heat at great depths is the uncertainty respecting the original law of temperature within the earth, before encrustation began. But it appears clearly and unmistakably that the true curve of temperature is much steeper than that resulting from the simple Fourier solution. At greater depths the steepness increases more and more, till it finally takes the form of the arc of an ellipse, as already pointed out. The curve is thus concave near the surface, and convex at great depths, so that it has a point of flexure, probably at no very great depth, but the exact location cannot be determined. The simple Fourier solutions always make the curves of temperature convex near the surface, which is a serious defect and introduces discontinuity at greater depths.

It may be noticed that when all the arguments of the times

$\tau_1, \tau_2, \tau_3, \dots \tau_i$ start from a common epoch $t=0$, and the functions $V, V', V'', \dots V^i$ are all equal, the subscripts in the right member of (32) drop out, and the equation reduces to

$$\Theta_i = \Theta + (\Theta - \Theta').$$

But in the more general problem the functions $\tau_1, \tau_2, \tau_3, \dots \tau_i$ date from i chosen epochs, and this gives the means of approximating any curve without change of flexure between $x=0$, and $x=x$.

§ 15. *Fourier's Methods Adequate for Effecting a Rigorous Solution of the Problem when the Conditions are Known.*

As already remarked the earth is so large and the crust so thin compared to the length of the radius, that the curvature of the surface may be neglected; and the layer of rock considered to extend to infinity in all directions, thus essentially conforming to Fourier's hypothesis of an infinite solid in the form of a flat plane.

Reasons have been assigned for doubting the great age sometimes ascribed to the earth, and it might seem like a waste of effort to draw the curves for the Fourier solutions in the case of such immense periods as 1000 million years; but in view of the great uncertainty heretofore prevailing in regard to the age of the consolidation it appeared advisable to conduct the investigation on the broadest lines. The leading characteristics of these Fourier solutions are shown by the rate of increase of temperature downward, and by the depth at which high temperature is attained. The horizontal scale, representing the depth, is the same in all the curves shown in the diagram; and thus a direct comparison of the effects of the three different periods is possible. In the case of the 1000 million year period the cooling has extended to great depth, more than 445 miles, which exceeds one tenth of the radius; in fact the increase continues downward to about 570 miles, or nearly 0.15 of the radius; but the change of temperature so deep down is excessively slow.

The curves for 100 million years after the initial epoch are naturally much steeper than those just considered, and accord closely with those drawn by Lord Kelvin, who used the same period. In the solution for the interval of 10 million years after the cooling began the curves are naturally very much steeper yet. In fact for this short period the cooling has not yet extended much lower than

40 miles, or about one tenth of that found for the 1000 million year period. The short period thus gives rapid rise of temperature near the surface, while the long periods give slow augmentation of temperature extending to great depths. All the Fourier curves, those for the rate of increase as well as for the temperature, become asymptotic to certain lines, as shown in the diagrams.

We have already considered how to pass from these Fourier solutions to a double solution which will take account of the increase of temperature downward at the initial epoch. This method of superposed or multiple solutions may be applied to all cases, but it has not seemed worth while to consider any case except that with a period of 10 million years and a surface temperature of 2000° . Whether we use the pure Fourier solution, or the compound produced by superposing two solutions of different period, it appears that the actual temperature increases at a nearly uniform rate for a depth of more than 40 miles, after which it is probable that the approximate elliptical law holds true to the center of the planet.

The temperature ellipse is not imagined to extend into the cooled crust, but to begin at the lower boundary of this layer. As we have treated of a superposition of two solutions of different periods, so also we might have compounded three, four or more solutions, with as many independent periods, which would enable us to represent any steady and continuous law of temperature within the earth. If this procedure is justifiable, it will follow that the uniform rise of temperature is nearly maintained for at least a tenth of the radius. Under the circumstances it is not to be hoped that any deviation from the uniform rate of increase near the surface will ever be discovered from experimental measurements of underground temperature. And observations indicating unequal rates at various depths are to be explained by the unequal conductivity of the different layers of the crust, and by fissures filled with hot lava during earthquakes of past geological ages.

From Fig. *D*, in the diagram, we see the principle of the multiple solution illustrated. The difference between the middle and lower curve is the effect of an additional 10 million years. This depression with changed sign should therefore be added to the simple Fourier solution to give the temperature curve under the hypothesis that

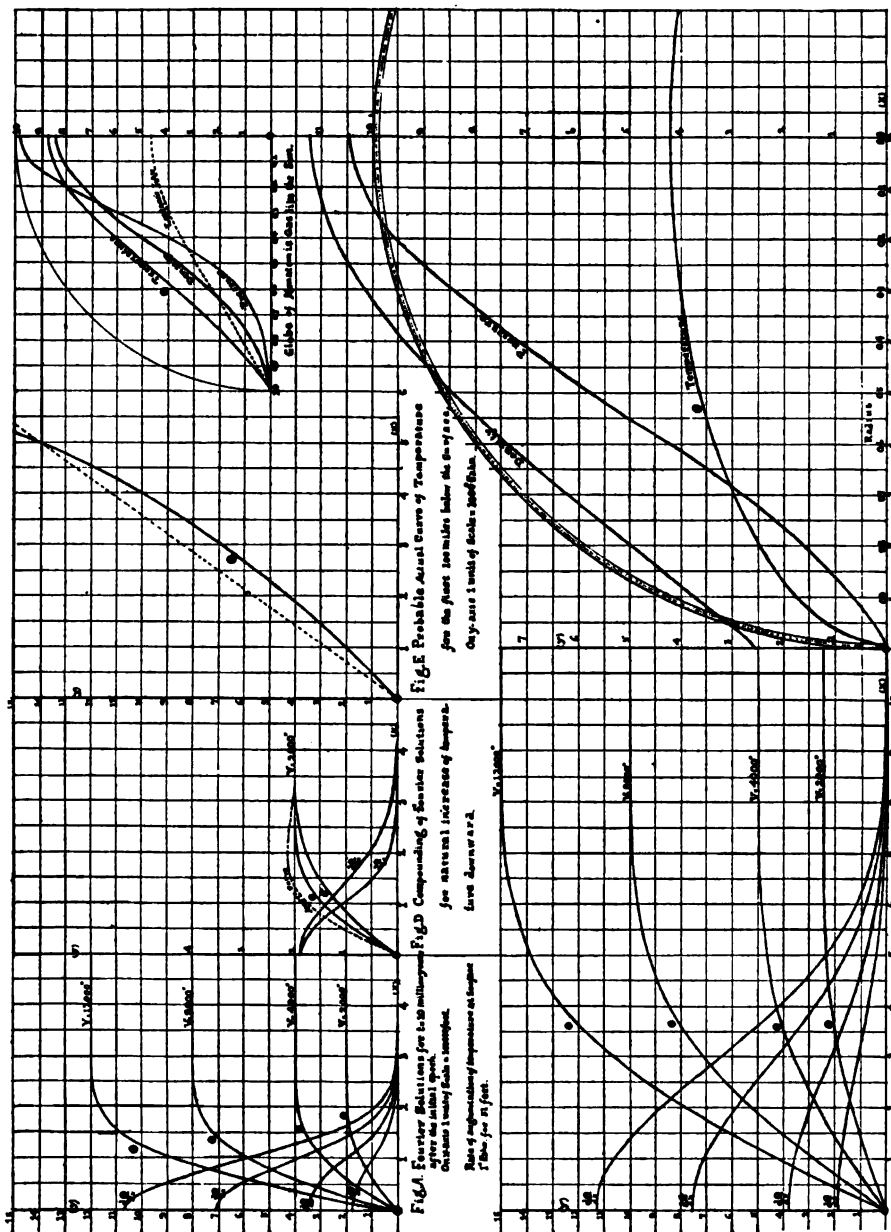
there is both a uniform temperature and an independent gradient equivalent to the effects of 10 million years of cooling.

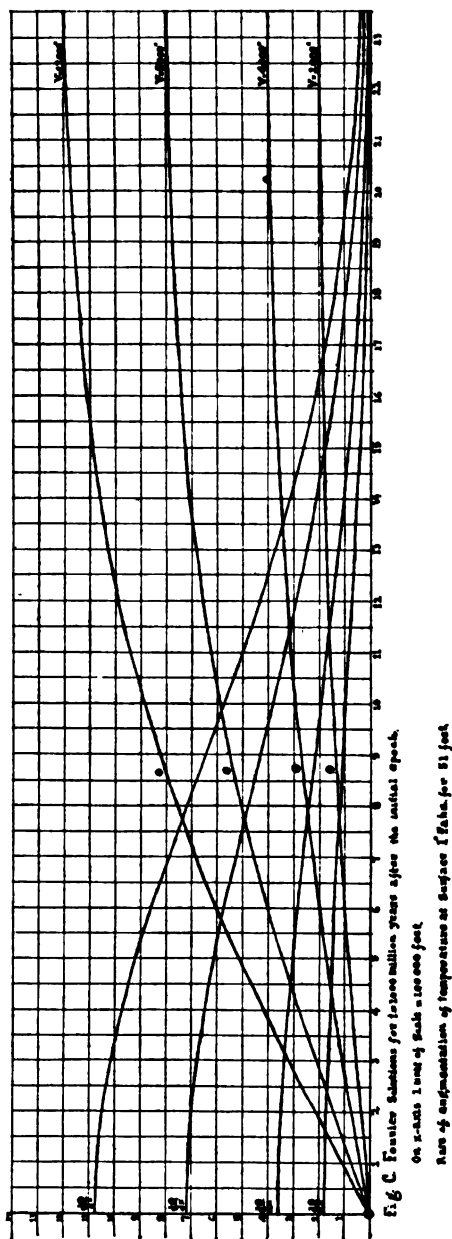
§ 16. *Various Methods for Determining the Depth to Which Cooling has Extended.*

Owing to the causes already indicated it seems reasonably certain that the cooling of the earth has not extended to any great depth. Moreover the original temperature gradient increasing with the depth still exists, but the flow of heat has changed the form of the curve. It will doubtless strike many as a somewhat remarkable fact that Professor Milne finds from earthquake observations that a fairly abrupt transition in the constitution of the crust occurs at a depth of about 30 miles (Bakerian Lecture, *Proc. Roy. Soc.*, 1906, p. 369). A depth of 45 miles was fixed upon for this transition by the Hon. R. J. Strutt, from certain considerations arising in his researches on radium (*Proc. Roy. Soc.*, Vol. 77, 1906, p. 483). Mr. R. D. Oldham finds that below this layer of crust the material of the globe seems to be fairly uniform until we reach great depth, about 0.4 of the radius from the center, where the change in the rate of propagation of earthquake waves shows that some discontinuity intervenes. Strutt remarks that the matter of the interior can scarcely consist mainly of iron, as has been commonly supposed, because with a thin crust of rock this would make the earth's mean density too great.

The ascertained depth of earthquake shocks and the observed rate of propagation of seismic waves both indicate a thin crust, but the phenomena of wave propagation make the thickness of the crust somewhat greater than that derived from the observed depth of earthquake disturbances. This suggests that earthquakes do not originate entirely beneath the crust, but chiefly in its lower layers. From Milne's results we seem justified in concluding that the cooling has not extended much if any below 40 miles, or 1/100th of the radius. The material below that depth acquires its properties mainly from the pressure to which it is subjected.

We have already considered the extension of Fourier's method which would enable us to approximate the true conditions near the surface; and it only remains to add that at greater depths there is a transition to the elliptical law, which holds approximately throughout the nucleus as a whole. There is obviously some uncertainty about





the exact path of the temperature curve where it passes through the layers just beneath the crust. The only condition one can be sure of is that it shall be everywhere continuous and have no change of flexure. It is outwardly concave near the surface, and it must remain so till we reach the arch of the ellipse. In the diagram for the earth's temperature we have drawn this curve according to what seemed to be its most probable course.

It is interesting to observe what the effect of this change of temperature near the surface is on the analysis of Lord Kelvin. We have

$$\frac{d\Theta}{dx} = \frac{V}{\sqrt{\pi\kappa t}} e^{-\frac{x^2}{4\kappa t}}.$$

And it appears that if the temperature increases more rapidly as we go downward, V would be larger for given depth, and the gradient near the surface would be steeper. The same effect could be produced by shortening the time t without changing the value of V . We have adopted this course as the most probable in the treatment of the question given above.

Also since

$$V = \frac{(\Theta - \Theta_0)\sqrt{\pi}}{2 \int_0^{\frac{x}{2\sqrt{\kappa t}}} e^{-z^2} dz},$$

V would be changed by changing the limits of the integral, or by modifying the value of Θ . But the integral depends only on x and t , and when these do not change appreciably it is most natural to depart from Fourier's solution by change of Θ .

IV. ON THE THEORY OF EARTHQUAKES HELD BY THE ANCIENTS.

§ 17. *On the Inaccessibility of the Views of the Greeks.*

Since Science is the outgrowth of successive revolutions of thought in the course of centuries, it is unfortunate that the views of the Greeks and Romans on many questions are not always accessible to modern readers. It is chiefly by a survey of human thought over long periods that one is enabled to form a clear conception of what has been done in a given subject. Too few students of science

have been able to make an adequate examination of the theory of earthquakes held by the Greeks.

The great multiplicity of subjects in our day, with the resulting unfortunate departure of education from the classic standard, has rendered the original languages of the best ancient authors well-nigh unintelligible to many men of science, because good translations are seldom accessible. One not infrequently meets with surprise even on the part of men of eminence and originality that anything valuable should be found in the writings of the Greeks and Romans.

A masterly grasp of the ancient languages on the part of men of science perhaps is not to be expected, but unfamiliarity with the general spirit of Greek thought is a serious inconvenience, because this defect often leaves the investigator without an adequate view of his own subject. There may thus arise a lack of reverence for the learning of the ancients, because their works are not understood. The poems of Homer and Sophocles, the eloquence of Demosthenes and Cicero, the sculptures of Phidias and Praxiteles, the paintings of Polygnotus and Apelles, the medical knowledge of Hippocrates and Galen, the philosophy of Plato and Aristotle, the astronomical researches of Hipparchus and Ptolemy, the mathematical discoveries of Apollonius and Archimedes—these and many other wonders of antiquity are not calculated to excite a contemptible opinion of the achievements of the Greeks. The perfection of their intellectual labors is attested by the great writers of all subsequent ages, and in modern times by none more amply than by Humboldt and Lyell, who did so much for the foundation of geology.

But while there has been some interest in the theories of the ancients, it has seemed of late years to have become more desultory, which must be ascribed chiefly to the inaccessibility of their works. The English reader possesses the well known translations of Bohn's Classical Library, which often have decided merit; but unfortunately they do not include all the works of Aristotle, the foremost physical philosopher among the Greeks, and the greatest thinker of the ancient times. He included his discussion of earthquakes in the treatise on meteorology, which has never been put into an accessible English translation. Taylor's translation lacks in scholarship, and was limited to fifty copies.

Strange as it may seem at first sight, it is owing principally to the wide grasp and characteristic penetration of Aristotle that he correctly put his discussion of earthquakes in the book which treats of the phenomena of the air. For he observed the connection between earthquakes and volcanoes as clearly as any modern man of science could do; and having noticed that in eruptions vapors escape from the earth and diffuse themselves in the atmosphere, he justly concluded that earthquakes are due to the action of pent-up vapors, even when they do not break through and escape to the surface. Could Newton, Laplace, Fourier or any modern investigator reason better than Aristotle has done on this point? In spite of some inevitable errors, due to the early time in which he lived, the penetration which he shows must be indeed a matter of surprise to all thoughtful students of the physics of the earth.

It is obvious that one should not expect from the Greeks and Romans highly finished theories, such as we find in some branches of modern science. If their thought was characterized by general soundness, it may justly excite our wonder. For with all the advantages of the vast learning of our time and the experience of centuries, we cannot claim that the moderns have always been equally fortunate. For example, in speaking of Tycho Brahé, Laplace justly remarks that notwithstanding his great genius for making astronomical observations he had little understanding for physical causes, on which the science of the heavens might be established; and the same remark applies to all except a few of the total number of investigators of subsequent time.

However many working hypothesis may be imagined, it is clear that no real science can be developed until the true physical cause of a phenomenon is discovered. So difficult is the discovery of causes that in speaking of Posidonius, Strabo ("Geog.," Lib. II., Chap. Iv., § 2) says that "he (Posidonius) is much too fond of imitating Aristotle's propensity for diving into *causes*, a subject which we (Stoics) scrupulously avoid, simply because of the extreme darkness in which all *causes* are enveloped." This remark enables one to understand why Aristotle, Posidonius and Archimedes stand so pre-eminent among the ancients.

Although the Romans had ample political and military instincts,

it is generally recognized that they had very inadequate scientific and philosophic intuition; their philosophers therefore adopted the theories of the Greeks, whose genius they admired. They copied and preserved, but added little to, the treasures of their intellectual masters. Thus Aristotle's explanations are incorporated into the writings of Seneca and Pliny. Aristotle himself gives the history of thought up to his time; and as Strabo was the most important of the later Greek writers on the theory of the world, while Pliny takes the foremost place among corresponding Roman authors, we have in the writings of these three great naturalists a comprehensive digest of the views of antiquity.

Although in his youth Aristotle was trained under Plato, in his later period he composed all his work in a condensed and direct style, without any of the allegorical symbolism so much used by the founder of the Academy. As his death was somewhat premature, at the age of about 63, it is thought by scholars that most all his works were left unfinished. Strabo gives the following account of the vicissitudes of Aristotle's manuscripts:

"The Socratic philosophers, Erastus, Coriscus and Neleus, the son of Coriscus, a disciple of Aristotle, and Theophrastus, were natives of Scepsis. Neleus succeeded to the possession of the library of Theophrastus, which included that of Aristotle; for Aristotle gave his library, and left his school, to Theophrastus. Aristotle was the first person with whom we are acquainted who made a collection of books, and suggested to the kings of Egypt the formation of a library. Theophrastus left his library to Neleus, who carried it to Scepsis, and bequeathed it to some ignorant persons who kept the books locked up, lying in disorder. When the Scepsians understood that the Attalic kings, on whom the city was dependent, were in eager search for books, with which they intended to furnish the library at Pergamus, they hid theirs in an excavation under ground; at length, but not before they had been injured by damp and worms, the descendants of Neleus sold the books of Aristotle and Theophrastus for a large sum of money to Appellicon of Teos. Appellicon was rather a lover of books than a philosopher; when therefore he attempted to restore the parts which had been eaten and corroded by worms, he made alterations in the original text and introduced them into new copies; he moreover supplied the defective parts unskillfully, and published the books full of errors. It was the misfortune of the ancient Peripatetics, those after Theophrastus, that being wholly unprovided with the books of Aristotle, with the exception of a few only, and those chiefly of the exoteric (popular) kind, they were unable to philosophize according to the principles of the system, and merely occupied themselves in elaborate discussions on commonplaces. Their successors, however, from the time

that these books were published, philosophized, and propounded the doctrines of Aristotle more successfully than their predecessors, but were under the necessity of advancing a great deal as probable only, on account of the multitude of errors contained in the copies.

"Even Rome contributed to this increase of errors; for immediately on the death of Apellicon, Sylla, who captured Athens, seized the library of Apellicon. When it was brought to Rome, Tyrannion, the grammarian, who was an admirer of Aristotle, courted the superintendent of the library and obtained the use of it. Some venders of books, also, employed bad scribes and neglected to compare the copies with the original. This happens in the case of other books which are copied for sale both here and at Alexandria." (Strabo's "Geography," XIII., Cap. 1, § 54; Bohn's Transl., Vol. II., pp. 378-380.)

There are naturally many points in regard to the writings of Aristotle on which scholars are not agreed, but since according to this account the entire works of Aristotle from his own manuscripts were first published at Rome during Strabo's lifetime, the substantial accuracy of the above statement can hardly be questioned. It is gratifying to find that, so far as one can now judge, Aristotle's views on earthquakes do not seem to have suffered any material corruption during the many centuries through which they have been transmitted to us. We may safely infer this from the theory as given by Strabo, soon after the publication of Aristotle's works, and from the theory given by Pliny, who had access to the writings of both Aristotle and Strabo, compared to the original Aristotelian doctrines set forth in the book on "Meteorology," the authenticity of which is unquestioned.

§ 18. *The Theory of Plato.* (427-347 B. C.)

As Plato was the teacher of Aristotle, but is not quoted in the account given in the "Meteorology," it seems likely that the expressions in Plato's works may be worthy of notice. The following citations are from Jowett's Translations of Plato's Dialogues.

In the *Phaedo* Plato gives the following discussion between Socrates and Simmias:

"'That,' said Simmias, 'will be enough.'

"'Well, then,' he said, 'my conviction is that the earth is a round body in the center of the heavens, and therefore has no need of air or any similar force as a support, but is kept there and hindered from falling or inclining any way by the equability of the surrounding heaven and by her own equipoise. For that which, being in equipoise, is in the center of that which is

equally diffused, will not incline any way in any degree, but will always remain in the same state and not deviate. And this is my first notion.'

"Which is surely a correct one," said Simmias.

"Also I believe that the earth is very vast, and that we who dwell in the region extending from the river Phasis to the Pillars of Herakles, along the borders of the sea, are just like ants or frogs about a marsh, and inhabit a small portion only, and that many others dwell in many like places. For I should say that in all parts of the earth there are hollows of various forms and sizes, into which the water and the mist and the air collect; and that the true earth is pure and in the pure heaven, in which also are the stars—that is the heaven which is commonly spoken of as the ether, of which this is but the sediment collecting in the hollows of the earth. But we who live in these hollows are deceived into the notion that we are dwelling above on the surface of the earth; which is just as if a creature who was at the bottom of the sea were to fancy that he was on the surface of the water, and that the sea was a heaven through which he saw the sun and the other stars—he having never come to the surface by reason of his feebleness and sluggishness, and having never lifted up his head and seen, nor ever heard from one who had seen, this other region which is so much purer and fairer than his own. Now this is exactly our case: for we are dwelling in a hollow of the earth, and fancy that we are on the surface; and the air we call the heaven, and in this we imagine that the stars move. But this is also owing to our feebleness and sluggishness, which prevent our reaching the surface of the air: for if any man could arrive at the exterior limit, or take the wings of a bird and fly upward, like a fish who puts his head out and sees this world, he would see a world beyond; and, if the nature of man could sustain the sight, he would acknowledge that this was the place of the true heaven and the true light and the true stars. For this earth, and the stones, and the entire region which surrounds us are spoilt and corroded, like the things in the sea which are corroded by the brine; for in the sea too there is hardly any noble or perfect growth, but clefts only, and sand, and an endless slough of mud: and even the shore is not to be compared to the fairer sights of this world. And greater far is the superiority of the other. Now of that upper earth which is under the heaven, I can tell you a charming tale, Simmias, which is well worth hearing.'

"And we, Socrates," replied Simmias, 'shall be charmed to listen.'

"The tale, my friend," he said, 'is as follows. In the first place, the earth, when looked at from above, is like one of those balls which have leather coverings in twelve pieces, and is of divers colors, of which the colors which painters use on earth are only a sample. But there the whole earth is made up of them, and they are brighter far and clearer than ours; there is a purple of wonderful luster, also the radiance of gold, and the white which is in the earth is whiter than any chalk or snow. Of these and other colors the earth is made up, and they are more in number and fairer than the eye of man has ever seen; and the very hollows (of which I was speaking) filled with air and water are seen like light flashing amid the other colors, and have a color of their own, which gives a sort of unity to the variety of earth. And in this fair region everything that grows—trees, and flowers, and fruits—

is in a like degree fairer than any here; and there are hills, and stones in them in a like degree smoother, and more transparent, and fairer in color than our highly valued emeralds and sardonyxes and jaspers, and other gems, which are but minute fragments of them: for there all the stones are like our precious stones, and fairer still. The reason of this is that they are pure, and not, like our precious stones, infected or corroded by the corrupt briny elements which coagulate among us, and which breed foulness and disease both in earth and stones, as well as in animals and plants. They are the jewels of the upper earth, which also shines with gold and silver and the like, and they are visible to sight and large and abundant and found in every region of the earth, and blessed is he who sees them. And upon the earth are animals and men, some in a middle region, others dwelling about the air as we dwell about the sea; others in islands which the air flows round, near the continent: and in a word, the air is used by them as the water and the sea are by us, and the ether is to them what the air is to us. Moreover, the temperament of their seasons is such that they have no disease, and live much longer than we do, and have sight and hearing and smell, and all the other senses, in far greater perfection, in the same degree that air is purer than water or the ether than air. Also they have temples and sacred places in which the gods really dwell, and they hear their voices and receive their answers, and are conscious of them and hold converse with them, and they see the sun, moon, and stars as they really are, and their other blessedness is of a piece with this.

“Such is the nature of the whole earth, and of the things which are around the earth; and there are divers regions in the hollows on the face of the globe everywhere, some of them deeper and also wider than that which we inhabit, others deeper and with a narrower opening than ours, and some are shallower and wider; all have numerous perforations, and passages broad and narrow in the interior of the earth, connecting them with one another; and there flows into and out of them, as into basins, a vast tide of water, and huge subterranean streams of perennial rivers, and springs hot and cold, and a great fire, and great rivers of fire, and streams of liquid mud, thin or thick (like the rivers of mud in Sicily, and the lava-streams which follow them), and the regions about which they happen to flow are filled up with them. And there is a sort of swing in the interior of the earth which moves all this up and down. Now the swing is in this wise. There is a chasm which is the vastest of them all, and pierces right through the whole earth; this is that which Homer describes in the words,—

“Far off, where is the inmost depth beneath the earth”; and which he in other places, and many other poets, have called Tartarus. And the swing is caused by the streams flowing into and out of this chasm, and they each have the nature of the soil through which they flow. And the reason why the streams are always flowing in and out is that the watery element has no bed or bottom, and is surging and swinging up and down, and the surrounding wind and air do the same; they follow the water up and down, hither and thither, over the earth—just as in respiring the air is always in process of inhalation and exhalation; and the wind swinging with the water in and out produces fearful and irresistible blasts: when the waters retire with a

rush into the lower parts of the earth, as they are called, they flow through the earth into those regions, and fill them up as with the alternate motion of a pump, and then when they leave those regions and rush back hither, they again fill the hollows here, and when these are filled, flow through subterranean channels and find their way to their several places, forming seas, and lakes, and rivers, and springs. Thence they again enter the earth, some of them making a long circuit into many lands, others going to few places and those not distant, and again fall into Tartarus, some at a point a good deal lower than that at which they rose, and others not much lower, but all in some degree lower than the point of issue. And some burst forth again on the opposite side, and some on the same side, and some wind round the earth with one or many folds, like the coils of a serpent, and descend as far as they can, but always return and fall into the lake. The rivers on either side can descend only to the center and no further, for to the rivers on both sides the opposite side is a precipice.

“Now these rivers are many, and mighty, and diverse, and there are four principal ones, of which the greatest and outermost is that called Oceanus, which flows round the earth in a circle; and in the opposite direction flows Acheron, which passes under the earth through desert places, into the Acherusian lake: this is the lake to the shores of which the souls of the many go when they are dead, and after waiting an appointed time, which is to some a longer and to some a shorter time, they are sent back again to be born as animals. The third river rises between the two, and near the place of rising pours into a vast region of fire, and forms a lake larger than the Mediterranean Sea, boiling with water and mud; and proceeding muddy and turbid, and winding about the earth, comes among other places, to the extremities of the Acherusian lake, but mingles not with the waters of the lake, and after making many coils about the earth plunges into Tartarus at a deeper level. This is that Pyriphlegethon, as the stream is called, which throws up jets of fire in all sorts of places. The fourth river goes out on the opposite side, and falls first of all into a wild and savage region, which is all of a dark-blue color, like lapis lazuli; and this is that river which is called the Stygian river, and falls into and forms the lake Styx, and after falling into the lake and receiving strange powers in the waters, passes under the earth, winding round in the opposite direction to Pyriphlegethon, and meeting in the Acherusian lake from the opposite side. And the water of this river too mingles with no other, but flows round in a circle and falls into Tartarus over against Pyriphlegethon; and the name of this river, as the poets say, is Cocytus.”

In the *Timeus* Plato represents a priest of Sais in Egypt as saying to Solon:

“There have been and will be again, many destructions of mankind arising out of many causes; the greatest have been brought about by the agencies of fire and water, and other lesser ones by innumerable other causes. There is a story which even you have preserved, that once upon a time Phaethon, the son of Helios, having yoked the steeds of his father's chariot, because he was not able to drive them in the path of his father, burnt up all that was

upon the earth, and was himself destroyed by a thunderbolt. Now this has the form of a myth but really signifies a declination of the bodies moving in the heavens around the earth, and a great conflagration of things upon the earth, which recurs after long intervals; at such times those who live upon the mountains and in dry and lofty places are more liable to destruction than those who dwell by rivers or on the seashore. And from this calamity the Nile, who is our never failing saviour, delivers and preserves us. When on the other hand, the gods purge the earth with a deluge of water, the survivors in your country are herdsmen and shepherds who dwell in the mountains, but those who, like you, live in cities are carried by the rivers into the sea. . . .”

Plato continues the discourse and finally tells of the sinking of the islands of Atlantis by an earthquake :

“Many great and wonderful deeds are recorded of your state in our histories. But one of them exceeds all the rest in greatness and valour. For these histories tell of a mighty power which unprovoked made an expedition against the whole of Europe and Asia, and to which your city put an end. This power came forth out of the Atlantic Ocean, for in those days the Atlantic was navigable; and there was an island situated in front of the straits which are by you called the pillars of Herakles; the island was larger than Libya and Asia put together, and was the way to other islands, and from these you might pass to the whole of the opposite continent which surrounds the true ocean; for this sea which is within the Straits of Herakles is only a harbor, having a narrow entrance, but that other is a real sea, and the surrounding land may be most truly called a boundless continent. Now in this island of Atlantis there was a great and wonderful empire which had rule over the whole island and several others, and over parts of the continent, and, furthermore, the men of Atlantis had subjected the parts of Libya within the columns of Herakles as far as Egypt, and of Europe as far as Tyrrhenia. This vast power, gathered into one, endeavored to subdue at a blow our country and yours and the whole of the region within the straits; and then, Solon, your country shone forth, in the excellence of her virtue and strength, among all mankind. She was preeminent in courage and military skill, and was the leader of the Hellenes.

“And when the rest fell off from her, being compelled to stand alone after having undergone the very extremity of danger, she defeated and triumphed over the invaders, and preserved from slavery those who were not yet subjugated, and generously liberated all the rest of us who dwell within the pillars. But afterwards there occurred violent earthquakes and floods, and in a single day and night of misfortune all your warlike men in a body sank into the earth, and the island of Atlantis in like manner disappeared in the depths of the sea. For which reason the sea in those parts is impassable because there is a shoal of mud in the way; and this was caused by the subsidence of the island.”

This account clearly shows that Plato ascribed to earthquakes the power to cause the submergence of land beneath the sea. As he was an excellent geologist for his time, he no doubt accepted also

the doctrine of the upheaval of the land by earthquakes. Aristotle distinctly states that these calamities are forgotten and lost from memory by the migrations of peoples and the ravages of time, and Plato clearly holds the same view.

§ 19. *The Theory of Aristotle* (384–322 B. C.).

The English translation given below is based on the Greek Text employed in the Tauchnitz edition of the works of Aristotle. The "Meteorology" is acknowledged to be a genuine production of the Stageirite, and the chief difficulty in translating it consists in the peculiar terminology and terseness of style used in this probably unfinished work. After the present translation was outlined the Rev. Theodore F. Burnham, M.A., very kindly read it and offered a number of valuable suggestions based on his extensive knowledge of Greek. Professor Edward B. Clapp, head of the Department of Greek in the University of California, also favored the translator with valuable criticisms, and very kindly supplied a copy of the scholarly French Translation by Barthelemy Saint-Hilaire, for the purpose of comparison in the final revision. As Aristotle's style is somewhat unique and peculiar to himself, this was felt to be important as a necessary precaution to ensure accuracy, especially where the language of the author is unduly condensed or incomplete, and therefore not easily interpreted.

Aristotle held that the air is produced from the evaporation of water ("Meteor.," Lib. I., Chap. 3) by the fire inside and outside the earth, and says that the air is a kind of vapor. He recognized that air could be heated by rapid and violent motion, and as arranged his adopted system of the world was made up of a lithosphere, a hydrosphere, an atmosphere, a pyrosphere and then beyond all the sphere of ether; certain interchanges took place between these divisions of the world.¹ Aristotle uses separate words for the various

¹ Among the many other points discussed by Aristotle we may mention the following:

1. The primitive fluidity of the globe. He holds, with Thales, that both the earth and sea were originally liquid; that a part was dried up by the sun. Indeed the wise men held that the sea was diminishing in volume by gradual desiccation, but Aristotle does not seem to hold this view. (Lib. II., Cap. I, § 1–4.)

2. The earth is spherical, not large, fixed in the center of the universe, causes night by its shadow in space, and also eclipses of the moon, the atmosphere being confined to this perishable sublunar sphere, as in the *Almagest* of Ptolemy, who often follows Aristotle.

phenomena connected with exhalations and vapors; ἡ ἀτμός for *steam*; τό πνεῦμα for a *blast* of wind or vapor; ἡ ἀναθυμίασις for *exhalation*; ὁ ἀνεμος for *wind*. The translation of πνεῦμα, meaning literally a *breath*, is very difficult, and seems best rendered by the phrase *blast* of wind or vapor, which seems to convey Aristotle's true meaning.

In the "Meteorology," Lib. I., Cap. 4, the following interesting passage occurs:

"It is not true, as they say, that the comet only appears in the north, even at the same time when the sun is in the summer tropic; for indeed the great comet which was seen at the time of the earthquake in Achaia, and the inundation of the sea wave, took its course from the setting of the equinoxes, and several others have been observed towards the south."

Again we read:

"The water which falls in rains drains away and nearly all filters into the earth. But there is in the earth a large amount of fire, and a great heat (ἵπάρχει δὲν τε τῇ γῇ πολὺ πῦρ πολλὴ θερμότης). (Lib. II., Cap. 4.)

Also:

"Thus when it rains, since the earth is dried by the heat which is in it and by that which has escaped above, an exhalation of vapor develops. This is the body of the wind (ἀνέμουν σώμα). And when this secretion is going on the winds blow. But when they cease because the heat, which is always secreted, is borne to the upper regions, the steam (ἡ ἀτμός) being cooled, condenses and becomes water; and when the clouds are collected in one place, and the surrounding cold penetrates them, water is formed and cools the dry exhalation" (τὴν ξηρὰν ἀναθυμίασιν). (Lib. II., Cap. 4.)

Aristotle's Theory of Earthquakes is as follows ("Meteorology," Lib. II., Cap. vii.):

"After these things (in relation to the winds) it is necessary to speak with reference to an earthquake and movement of the earth; for the cause of the phenomenon is closely connected with this (theory of the winds).

"Up to the present time there are three explanations of these phenomena, from three different authorities: Anaxagoras the Clazomenian, and before him Anaximenes the Milesian have each discussed them, and subsequently to these Democritus the Abderite.

"Now Anaxagoras holds that the ether when generated is naturally borne upward, and falling into the depths of the earth below, and the cavities, shakes it; and the upper parts of the earth in consequence of the rains are pressed together; and freely admitting that by its nature the earth is everywhere equally porous, he holds that the sphere has in its totality both an elevation and a base, the elevation being the part which we happen to inhabit and the base the other part.

"With reference to this subject then perhaps we ought to say nothing,

simply because it is too superficially proved. To understand the elevation and base in such a way that all the bodies which have weight would not at every place be borne to the earth, while the light bodies and the fire tend upward, is indeed most absurd; for this is going contrary to the evidence of our senses, which show us that the horizon of the habitable world, so far as we know it, varies constantly according to the extent which we ourselves change place, the earth being convex and spherical. To say that on account of its mass it remains in the air, and to maintain that the trembling of the earth arises when it is smitten from below upwards in its totality, is not less strange. Moreover, in these considerations, Anaxagoras takes no account of some circumstances which accompany earthquakes; for not all lands, nor all seasons participate in this commotion, by chance and indiscriminately.

"Democritus indeed holds that the matter of the earth is full of water, and receiving much other water from the rain storms, it is moved by this; but this arises more from the inability to hold (the water) in the yawning cavities, which, breaking forth violently, causes the shaking of the earth; and the ground being dry and drawing forth into the empty places water escaping from the reservoirs, gives rise to motion of sudden agitation.

"Anaximenes, on the other hand, holds that when moistened and afterwards dried out the earth is shattered to pieces, and is shaken from the sinking in of fragments of the hills; from which also arises the earthquakes in the dry, and likewise in the wet, seasons; for in droughts, just as is said, the dry ground is cracked open, and the overmoist earth, produced by the absorption of the waters, subsides. If that happens which is agreeable to the theory of Anaximenes one should observe in many places the earth caving in. Yet by what cause the phenomenon arises in certain places, no one opinion carries extreme weight of authority relatively to others; nevertheless such a claim was put forth.

"This explanation supposes necessarily that earthquakes always become less and less powerful, and finally cease to vibrate. That which settles down ought to do so naturally. Consequently if this is impossible, it is very evident that it can not be the true cause of the phenomenon.

"CAP. VIII.

"But since it manifestly is a necessity, that exhalation of vapor should be produced all the time, both from the moisture and from the dryness, as we have said in what precedes, it is likewise necessary that from these antecedents earthquakes should be produced; for in itself the earth is dry, yet on account of the rains, acquires in its interior much moisture; so that having been warmed by the sun, and the internal fire, largely indeed from without, but also largely from within, the blast of vapor is developed; and this blast when it sometimes escapes externally flows in a continuous manner; and likewise sometimes when it escapes within the earth; and then again it is scattered. If then this can not take place otherwise, we must consider what among all these bodies, is the most capable of producing the motion; this is necessarily that which naturally goes farthest, and is most violent, but especially of this latter nature.

"Now the most violent is of necessity that which moves the most rapidly;

for it communicates violence principally through the rapid speed. But the body which goes farthest, is that which most easily traverses all things; and it is the lightest body which is able to do this. Consequently since the nature of the air itself is the lightest, it is the blast of wind which most powerfully moves all bodies; for the fire, whenever accompanied by a blast of wind, produces a flame, and it is borne rapidly. Therefore is it neither the water, nor the earth which is the cause of the shaking, but the blast of wind, whenever the evaporation without may have again accumulated within (the earth). Hence in a calm arise the most and the largest earthquakes; for the exhalation being naturally continuous it follows that in general it will develop with the very first agitation of the cause. Consequently either from within the earth all at once, or from without by a violent impulse, the whole body of vapor rushes en masse. But that some earthquakes should be produced, coincident with a dominant blast of wind is not strange; for we sometimes see several winds blowing together; from this circumstance, whenever one strikes the earth more violently than the other while the blast is blowing an earthquake takes place. But these give rise to tremors of inferior magnitude, because their principle and cause are separated.

"Now the larger number and greatest earthquakes occur by night; those of the day about noon; for the calmest time of the day in general is at noon; for the sun then, when of the greatest power, confines the vapors to the earth; and is most powerful about mid-day; and the nights of these days are calmest, on account of the absence of the sun: consequently there arises from within the earth a streaming movement like the ebb of the tides, in a sense contrary to the flow of the sea without; and this phenomenon generally develops about daybreak; it is at this time that the blasts ordinarily commence to blow. If therefore the force of them by chance turns quickly around, as Euripus (does), on account of the mighty tides of the sea, it produces an earthquake.

"Indeed it is about places of this kind that the mightiest of the earthquakes arise, where the sea is boisterous or the land is porous and cavernous. Wherefore they occur also about the Hellespont, and about Achaia, and Sicily, and about the analogous places of Eubœa; for the sea seems to pass through conduits under the earth. Hence also the warm springs around Aïdepsus are produced by the same cause. And around the aforesaid places the earthquakes arise chiefly on account of the narrowness of the conduits; for the current of wind, which ordinarily blows from the land, finds itself driven back by the fullness of the sea which in such places becomes violent.

"The localities which have such caverns below thereby retaining much vapor, are most shaken by earthquakes, and in the spring and the end of autumn principally, and they rise both in the rainy and the dry seasons from the same cause; for these are the seasons in which there is most blowing of wind; in fact both summer and winter, the one by the frigidity and the other by the heat, produces calms; the one being exceedingly cold and the other exceedingly dry.

"Moreover in the dry seasons the air is very windy; for the dryness develops precisely when the dry exhalation is more considerable than the humidity; and in the rainy seasons the internal exhalation increases, and as it finds itself intercepted in very narrow places, and violently confined in a

less space because the cavities are full of water, the stream of wind begins to acquire the force for even the compression of its own bulk in this too limited space; and flowing out and striking against the passages the wind produces a violent earthquake; for it is necessary to bear in mind that, just as in our own body, the force of the breath held within produces a trembling and suffocation, so also in the earth the blast of vapor has an analogous effect; and that the shocks of earthquakes are partly of the nature of trembling and partly of suffocation, just as it often comes to pass after urination that a kind of vibration of the body is produced, a trembling with sudden drawing of the breath from without to the interior; thus arise also such phenomena with respect to the earth.

"In order to take proper account of all the influence which the blast of vapor exerts, it is necessary to observe not only what takes place in the air; for one can believe in the power of such things by their magnitude; but also what happens in the bodies of animals; convulsions and spasms are only motions of the breath, and they have such violence that often several persons uniting all their efforts are unable to keep the movements of the afflicted under control. Now it is necessary to bear in mind that the same thing happens also in the earth, since we naturally judge the great by reference to the small.

"Signs of these things, and according to our own observation, have occurred in many places; for the shaking of the earth arising in certain localities does not cease till the agitating wind has escaped freely into the region above the earth like the blast of a hurricane; it is not long ago since this actually happened at Heraclea in Pontus, and formerly at the island of Hiera, which is one of the islands called after Æolus; in this some earth swelled up, and with a loud noise rose in the form of a hill, and having finally broke forth, the mighty urging blast escaped and ejected sparks and ashes, which covered the region about the Lapari islands, spread over the whole land, and extended even to several cities in Italy: and at the present time where this eruption occurred is still evident; and now the development of fire in the earth must be held to have caused this, at the time of the first outbreak, the particles being reduced to the size of the finest dust of the air. Moreover, it is proved that blasts of vapor circulated beneath the earth, and that this occurred at these islands; for whenever the south wind starts to blow, there are first some premonitory signs of it; for places have it from which eruptions occur, because the sea is already agitated far and wide; and it again confines the swelling vapor within the earth, for the simple reason that the sea is spread over it.

"Accordingly it makes a noise without an earthquake, throughout the open spaces of these regions (imagined as deep conduits), either because the places are very vast, since above the earth they expend into immensity, or because the quantity of air expelled is very small.

"Moreover, the changes of the sun, which grows faint and dark without clouds, and the stillness and extreme cold, which sometimes precede the earthquakes occurring at daybreak are only additional signs of the aforesaid cause; for the sun must be obscured and darkened when the blast of vapor begins to sink within the earth, for dissolving and expelling the air,

and the winds must cease before dawn, and at daybreak, when the cold causes a stillness; for necessarily the stillness in most cases comes to pass, just as was also said before, because it is a reflex of the blast going within the earth, and happens especially before the greatest earthquakes; the blast of vapor is not much scattered, either that without or that within the earth, but borne along its course becomes at daybreak necessarily most violent.

"The cold comes to pass on account of the exhalation of the vapor circulating within, with all the heat naturally contained in it. If the winds do not seem to be warm it is because they move the air filled with cold vapor and considerable steam, just as in the case of the breath exhaled from the mouth; in fact this vapor is but slightly warm, as when we breathe; yet on account of the small amount of the air, the heat of it is not so evident; but further away the breath is cold from the same cause that the winds are.

"From the time that this force enters within the earth, the flowing away of the vapor combined with the moisture makes the cold, in places where this phenomenon is encountered. This is also the cause which ordinarily makes a sign before earthquakes; for whether by day, or a little after sunset, when the sky is clear, a faint cloud appears spreading and lengthening itself out, as a fine line perfectly straight, the blast of wind quieting down on account of the setting (of the sun). Whence similar phenomena come to pass also in the sea, about the shores; and especially whenever it is thrown into billowy waves, exceedingly violent and irregular, breakers at the beach are produced; but whenever a calm arises, because the breaking of the surface is very slight, the waves are small and regular.

"Accordingly that which the sea does around the land, the wind does about the dark clouds of vapor in the air. So that whenever the wind calms down, the cloud which remains is exactly a straight line and very tenuous, as if it were a mere wave of diffuse air.

"On account of these things therefore an earthquake is sometimes produced during the eclipses of the moon; for whenever the closing up of the earth between the sun and moon is near at hand, and the light is not yet indeed altogether gone, and the heat from the sun is still in the air, but already languishing, a calm arises by the wind suddenly whirling about and throwing itself in the earth, which produces the earthquake before eclipses; for the winds often arise before eclipses, winds at nightfall before eclipses at midnight, and winds at midnight before those at dawn. And this comes to pass on account of extinguishing the heat from the moon, whenever the event is already near; in which development the eclipse consists. That which holds the air and calms it having disappeared, it is agitated anew, and a blast of wind arises late in the evening previous to the eclipse.

"But whenever a powerful earthquake occurs it neither ceases immediately nor with a single disturbance; but sometimes it shakes for about forty days; upwards of one and even two years is indicated at certain places. The cause of the violence is the greatness and fullness of the blast of vapor, and the forms of the places from which it flows; that which it strikes against, but does not easily penetrate, shakes most; and it necessarily agitates in the narrow places, just as in the case of obstructed water which is not able to pass through. Wherefore just as in the body the inflamed throbbings do

not cease of a sudden, nor rapidly, but by gradual giving away, along with the decrease of the symptom, so likewise the cause that produces the exhalation of vapor, and the first shock of the blast, do not at once set free the matter, from which are developed the kind of wind, which we call an earthquake. Until therefore the rest of these vapors has escaped the shaking of the earth necessarily continues. But it acts more and more feebly, till the time when the exhalation is too reduced to make a movement which remains sensible.

"And the blast of vapor also makes those sounds which arise beneath the earth, and those which precede earthquakes. And even without earthquakes there are places where these noises are developed under the earth; for just as the air when struck and rent produces all kinds of noises, so likewise also the ground itself produces noises when shaken; for there is no difference, since in the shock everything which agitates is itself shaken in its entirety. The roaring precedes the commotion, because the sound has parts as tenuous as the wind itself, and it penetrates as easily through all bodies.

"And whenever it is unable to move the earth on account of its very lightness, it is certain, since it passes through without difficulty, that it does not make it tremble, but according as it strikes against hard substances with cavities, and all manner of shapes, so they give off all kinds of sounds; consequently it sometimes seems, just as the marvel-mongers say, that the earth is made to roar.

"Occasionally as the result of earthquakes water gushes forth from the ground; but one is not able to say on this account that it was the water which caused the commotion; on the contrary it is always the blast of wind, whether from the surface, or confined below the earth, that produces the violence; and this is the moving power, just as one may say that the winds develop waves in the sea but the waves are not the cause of the winds; and thus then one may say that this earth itself is the cause of the phenomenon; for having been shaken it oscillates, just as water does, for the wave is a kind of oscillation; but the cause of the phenomenon is the same in both (the water and the earth); it experiences the agitation, yet does not produce it; but the blast of vapor is the real cause.

"Wherever along with an earthquake an inundation is produced the cause of it is the development of blasts of wind of a contrary nature. This happens whenever the blast of wind which shakes the earth is unable to repel completely the sea, which another blast of wind controls, nevertheless meeting it, opposing it, and confining it, gathering much force at the same point; for then necessarily the blast of wind confined in the earth by the sea cannot be resisted from breaking open a passage against the force of the opposite blast, and making a cataclysm.

"This is exactly what happened in the region of Achaia; for above the earth there was the south wind on one side, the north wind on the other. A calm having arisen, and the wind flowing within, there was produced at the same time an inundation and the accompanying earthquake; and the violence arose chiefly because the sea would not give passage to the wind imprisoned under the earth, but on the contrary obstructed it. Then having forced open other passages, the blast of vapor produced the earthquake, and the rising of the great sea wave caused the cataclysm.

"On the other hand earthquakes are produced, and often extend over but a small area; yet the winds are not local in character; on the contrary they arise whenever the exhalations, those over the area itself, and those of the neighbouring region, act in concert; just as we say the droughts are produced, and the rainy seasons in turn at any given place. And the earthquakes are produced likewise in the very same manner; but it is not so for the winds, for all these phenomena (the earthquakes, droughts and rains) have their origin in the earth, in such a way that they work together; the power of the sun, however, is not similar, but is rather exerted upon those exhalations high above the earth, so that whenever they experience the influence of the sun's annual circuit, according to the differences of the places on the earth, they all flow together.

"Whenever there is therefore considerable exhalation it shakes the earth, as in a trembling to and fro; it occurs more rarely, and only in certain places, as a pulsation, oscillating up and down; wherefore also shocks of this kind are of slight intensity; for it is not easy for a body of the elements to join together in this movement; since the secretion of vapor is many times larger at the surface than at great depths. Wherever such an earthquake arises, there is a hurling forth of a multitude of stones, just as in the case of sand winnowed by the wind. In this manner, when such an earthquake occurred, ejection of stones took place in Sicily, in the region called the Phlegrean fields, and in the Ligurian country.

"And in the islands of the deep sea earthquakes occur less often than in the islands near the continents. The immensity of the sea cools the exhalations, and it hinders them and resists them by the weight which it imposes upon them. Moreover even when the winds blow the sea always oscillates, and is not shaken powerfully by the agitating blasts.

"But on account of the enormous space it occupies it is not in it, but from it that the exhalations are produced, and those from the earth follow them: and the islands lying close to the mainland are only a part of the mainland itself; the space between, on account of its smallness, being of no importance; but those islands in the sea cannot be moved without disturbing the whole sea, which is spread around them. So much therefore may be said in regard to earthquakes, and their nature, and the cause through which they arise, and the other most important circumstances closely associated with them."

DE MUNDO,¹ CAP. IV.

(Scholars do not consider this work a genuine production of Aristotle, but no doubt it represents the Peripatetic School of Philosophy.)

"A blast of vapor erupting from the earth is carried upwards from the depths below or from the yawning fissure; whenever it is borne with much whirling movement there is a terrestrial thunderstorm; the blast of vapor ascends to the clouds, dense and moist, and outwardly scatters violently the

¹ *περὶ κόσμου πρὸς Ἀλέξανδρον*. This must not be confused with the treatise on the heavens, which is entitled *περὶ οὐρανοῦ*.

collected mass of the cloud, and gives rise to a great noise and clashing, called thunder, just as in water (when heated) a blast of steam breaks forth violently. During the outbreak from the cloud the blast becomes fiery and brilliant, and is called lightning; it strikes before the thunder because it develops before it. . . .

"Now just as the earth includes within it a large amount of water, so likewise it contains also blasts of vapor, and streams of fire. And of these, those which are beneath the earth are obviously invisible; but many have vents, and eruptions, just as Lapari and Aetna and places in the islands of Æolus; which indeed often produce flows as in rivers and belch forth red hot streams of fire; some coming from beneath the earth, near springs of water, heat them, while others arise from springs of lukewarm character; the former being extremely hot, the latter agreeably tempered."

"And similarly many blasts of vapor break out from cavities everywhere in the earth; some of these communicate great enthusiasm to those who approach them, while others cause a languishing effect; and again others are made to sing oracles, as those in Delphi, and in Lebadia, and finally there are some which wholly destroy one another, just as those in Phrygia.

"And quite often also a blast of vapor conveniently tempered in the earth issues forth into its innermost passages, making strange sounds from familiar places, and a large part of the blast flows out. Very often also a strong blast of vapor arises from without, and is absorbed in the cavities of the earth, shutting off the escape, and with force shaking it, seeking to break open its own orifice, and producing the phenomena which we are accustomed to call an earthquake.

"And of earthquakes there are some which shake sidewise, at acute angles (obliquely), called *epiclintonæ*; those shaking upward and downward, at right angles, *brastæ*, those in which the ground collapses, making hollows, *chasmata*, those opening chasms and breaking the ground all to pieces, called *rhectæ*. And of all these, there are some which permit the escape of a blast of vapor; others which throw up stones; others which eject earth, some which disclose sources not suspected before; and still others returning to equilibrium after a single shock, which they call *ostæ*; those which rebound, the disturbed body oscillating to and fro, so as always to restore the equilibrium, such shaking is called *palmata*, which produces a phenomenon like a trembling.

"There arises also earthquakes with subterranean thunder, shaking the earth with a roaring noise. Very often apart from an earthquake there arises a roaring of the earth, whenever the vapor is not strong enough to shake it, but nevertheless circulates within, endowed with a powerful rotatory motion.

"There are likewise blasts of vapor which enter the earth's interior, and are absorbed by the waters hidden within the earth. These phenomena are analogous to those which occur in the sea; for there are also chasms where the sea opens out and again when it withdraws, and there is an inundation of waves, and they have a recoil; and occasionally there is only a single pushing away of the sea (*πρῶσις*), just as is related indeed of Helike and of Boura.

"Frequently there is also produced an eruption of fire from the sea, and a spouting up of springs, and a breaking forth of rivers, and an uprooting of trees, terrible eddies and whirlpools, analogous to those due to blasts of wind; some of these phenomena occur on the depths of the sea, others in Euripus and the straits near the land.

"Many ebbs and flows of waves are said to run in always with the moon, at certain well determined epochs. To speak of the whole in a few words, we may therefore say that the elements mixing together among themselves, in the air, the earth and the sea, there is only considerable probability of the similar properties combining together, bringing to diverse creatures death or life partially, but on the whole conserving the indestructible universe just as it is uncreated. . . .

"In reality terrible earthquakes have thrown in confusion many parts of the earth; the rains suddenly falling produce floods, and ominous outbreaks; inundations of waves, and recessions of the water makes sea where it was land and land where it was sea; the force of the winds and typhoons, are such as to overturn whole cities; volcanoes indeed and flames have broken out, which coming as of old from the heavens, just as they say since the time of Phaethon (driver of the sun's chariot), have burned up the parts towards the dawn; but on the other hand towards hesperus, they issue forth and radiate from the earth, just as the craters which have sent forth the flames of *Ætna*, and spreading over the ground are carried down as a torrent.

"It is in the terrible catastrophes arising from such an outpouring that the Diety has conspicuously honored the race of the pious who permit themselves to be surrounded by fiery streams of lava, when they take upon their shoulders their aged parents and save them; for when it nears them, the stream of fire, having developed as a river, divides, turning aside here, and again there, and spares the young persons along with their parents; without harming them. And in general, what the pilot is to the ship, the driver to the chariot, the leader to the choir, the law in the state, the general in the army, this the Diety is in the Cosmos."

§ 20. *The Theory of Strabo* (66 B. C.—24 A. D.).

The translation of Strabo's Geography included in Bohn's Library is acknowledged to be good; we shall therefore quote from it some extracts which exhibit Strabo's views. In the introduction to Strabo's "Geography" (Chap. III., § 3-4), this interesting passage occurs:

"Again, having discoursed on the advance of knowledge respecting the geography of the inhabited earth, between the time of Alexander and the period when he was writing, Eratosthenes goes into a description of the figure of the earth; not merely of the habitable earth, an account of which would have been very suitable, but of the whole earth, which should certainly have been given too, but not in this disorderly manner. He proceeds to tell us that the earth is spheroidal, not however perfectly so, inasmuch as it has certain irregularities, then enlarges on the successive changes of form, occasioned by water, fire, earthquakes, eruptions, and the like; all of which

is entirely out of place, for the spheroidal form of the whole earth is the result of the system of the universe, and the phenomenon which he mentions do not in the least change its general form; such little matters being entirely lost in the great mass of the earth. Still they cause various peculiarities in different parts of our globe, and result from a variety of causes.

"He points out as a most interesting subject for disquisition the fact of our finding, often quite inland, two or three thousand stadia from the sea, vast numbers of muscle, oyster, and scallop-shells, and salt-water lakes. He gives as an instance, that about the temple of Ammon, and along the road to it for the space of 3,000 stadia, there are yet found a vast amount of oyster shells, many salt-beds, and salt springs bubbling up, besides which are pointed out numerous fragments of wreck which they say have been cast up through some opening, and dolphins placed on pedestals with the inscriptions, Of the delegates from Cyrene. Herein he agrees with the opinion of Strato the natural philosopher, and Xanthus of Lydia. Xanthus mentioned that in the reign of Ataxerxes there was so great a drought, that every river, lake, and well was dried up: and that in many places he had seen a long way from the sea fossil shells, some like cockles, others resembling scallop shells, also salt lakes in Armenia, Matiana and Lower Phrygia, which induced him to believe that the sea had formerly been where the land now was. Strato, who went more deeply into the cause of these phenomena, was of opinion that formerly there was no exit to the Euxine as now at Byzantium, but that the rivers running into it had forced a way through, and thus let the waters escape into the Propontis, and thence to the Hellespont. And that a like change had occurred in the Mediterranean. For the sea being overflowed by the rivers, had opened for itself a passage by the Pillars of Hercules, and thus, much that was formerly covered by water, had been left dry. He gives as the cause of this, that anciently the levels of the Mediterranean and Atlantic were not the same, and states that a bank of earth, the remains of the ancient separation of the two seas, is still stretched under water from Europe to Africa. He adds, that the Euxine is the most shallow, and the seas of Crete, Sicily and Sardinia much deeper, which is occasioned by the number of large rivers flowing into the Euxine both from the north and east, and so filling it up with mud, whilst the others preserve their depth. This is the cause of the remarkable sweetness of the Euxine Sea, and of the currents which regularly set towards the deepest part. He gives it as his opinion, that should the rivers continue to flow in the same direction, the Euxine will in time be filled up (by the deposits), since already the left side of the sea is little else than shallows, as also Salmydessus, and the shoals at the mouth of the Ister, and the desert of Scythia, which sailors call the Breasts. Probably too the temple of Ammon was originally close to the sea, though now, by the continual deposit of the waters, it is quite inland: and he conjectures that it was owing to its being so near the sea that it became so celebrated and illustrious, and that it never would have enjoyed the credit it now possesses had it always been equally remote from the sea. Egypt too (he says) was formerly covered by sea as far as the marshes near Pelusium, Mount Casius, and the Lake Sirbonis. Even at the present time, when salt is being dug in Egypt, the beds are found under layers of sand and mingled

with fossil shells, as if this whole district had formerly been under water, and as if the whole region about Casium and Gerrha had been shallows reaching to the Arabian Gulf. The sea afterwards receding left the land uncovered, and the Lake Sirbonis remained, which having afterwards forced itself a passage, became a marsh. In like manner the borders of the Lake Mœris resemble a sea-beach rather than the banks of a river. Every one will admit that formerly at various periods a great portion of the mainland has been covered and again left bare by the sea. Likewise that the land now covered by the sea is not all on the same level, any more than that whereon we dwell, which is now uncovered and has experienced so many changes, as Eratosthenes has observed. Consequently in the reasoning of Xanthus there does not appear to be anything out of place.

"In regard to Strato, however, we must remark that, leaving out of the question the many arguments he has properly stated, some of those which he has brought forward are quite inadmissible. For first he is inaccurate in stating that the beds of the interior and the exterior seas have not the same level, and that the depth of the two seas is different; whereas the cause why the sea is at one time raised, at another depressed, that it inundates certain places and again retreats, is not that the beds have different levels, some higher and some lower, but simply this, that the same beds are at one time raised, at another depressed, causing the sea to rise or subside with them; for having risen they cause an inundation, and when they subside the waters return to their former places. For if it is so, an inundation will of course accompany every sudden increase of the waters of the sea, (as in the spring tides) or the periodical swelling of rivers, in the one instance the waters being brought together from distant parts of the ocean, in the other, their volume being increased. But the rising of the rivers are not violent and sudden, nor do the tides continue any length of time, nor occur irregularly; nor yet along the coast of our sea do they cause inundations nor anywhere else. Consequently we must seek for an explanation of the cause either in the stratum composing the bed of the sea, or in that which is overflowed; we prefer to look for it in the former, since by reason of its humidity it is more liable to shiftings and sudden changes of position, and we shall find that in these matters the wind is the great agent after all. But, I repeat it, the immediate cause of these phenomena, is not in the fact of one part of the bed of the ocean being higher or lower than another, but in the upheaving or depression of the strata on which the waters rest. Strato's hypothesis evidently originated in the belief that that which occurs in rivers is also the case in regard to the sea; viz. that there is a flow of water from the higher places."

Again in Chap. III., section 10:

"Some, however, may be disinclined to admit this explanation, and would rather have proof from things more manifest to the senses, and which seem to meet us at every turn. Now deluges, earthquakes, eruptions of wind, and risings in the bed of the sea, these things cause the rising of the ocean, as sinking of the bottom causes it to become lower. It is not the case that small volcanic or other islands can be raised up from the sea, and not large

ones, nor that all islands can, but not continents, since extensive sinkings of the land no less than small ones have been known; witness the yawning of those chasms which have engulfed whole districts no less than their cities, as is said to have happened to Bura, Bizone, and many other towns at the time of earthquakes: and there is no more reason why one should rather think Sicily to have been disjoined from the mainland of Italy than cast up from the bottom of the sea by the fires of Aetna, as the Lipari and Pithecussan Isles have been."

In Chap. III., sections 16 and 17, we read:

"In order to lessen surprise at such changes as we have mentioned as causes of the inundations and other similar phenomena which are supposed to have produced Sicily, the islands of Aeolus and the Pithecussae, it may be as well to compare with these others of a similar nature, which either now are, or else have been observed in other localities. A large array of such facts placed at once before the eye would serve to allay our astonishment; while that which is uncommon startles our perception, and manifests our general ignorance of the occurrence which takes place in nature and physical existence. For instance, supposing any one should narrate the circumstances concerning Thera and the Therasian Islands, situated in the strait between Crete and the Cyrenaic, Thera being itself the metropolis of Cyrene; or those (in connexion with) Egypt, and many parts of Greece. For midway between Thera and Therasia flames rushed forth from the sea for the space of four days; causing the whole of it to boil and be all on fire; and after a little an island twelve stadia in circumference, composed of the burning mass, was thrown up, as if raised by machinery. After the cessation of this phenomenon, the Rhodians, then masters of the sea, were the first who dared to sail to the place, and they built there on the island a temple to the Asphalian Neptune. Posidonius remarks, that during an earthquake which occurred in Phoenicia, a city situated above Sidon was swallowed up, and that nearly two thirds of Sidon also fell, but not suddenly, and therefore with no great loss of life. That the same occurred, though in a lighter form, throughout nearly the whole of Syria, and was felt even in some of the Cyclades and the Island of Euboea, so that the fountains of Arethusa, a spring in Chalcis, were completely obstructed, and after some time forced for themselves another opening, and the whole island ceased not to experience shocks until a chasm was rent open in the earth in the plain of Lelanto, from which poured a river of burning mud.

"17. Many writers have recorded similar occurrences, but it will suffice to narrate those which have been collected by Demetrius of Skepsis.

"Apropos of that passage of Homer:

"And now they reach'd the running rivulets clear,
Where from Scamandar's dizzy flood arise
Two fountains, tepid one, from which a smoke
Issues voluminous as from a fire,
The other, even in summer heats, like hail
For cold, or snow, or crystal stream frost-bound:"

"this writer tells us we must not be surprised, that although the cold spring still remains, the hot cannot be discovered; and says we must reckon the failing of the hot spring as the cause. He goes on to relate certain catastrophes recorded by Democles, how formerly in the reign of Tantalus there were great earthquakes in Lydia and Ionia as far as the Troad, which swallowed up whole villages and overturned Mount Sipylus; marshes then became lakes, and the city of Troy was covered by the waters. Pharos, near Egypt, which anciently was an island, may now be called a peninsula, and the same may be said of Tyre and Clazomenæ."

In Chap. III., section 18:

"Of Bura and Helice, one has been swallowed by an earthquake, the other covered by the waves. Near to Methone, which is on the Hermionic Gulf, a mountain seven stadia in height was cast up during a fiery eruption; during the day it could not be approached on account of the heat and sulphureous smell; at night it emitted an agreeable odour, appeared brilliant at a distance, and was so hot that the sea boiled around it to a distance of five stadia, and appeared in a state of agitation for twenty stadia, the heap being formed of fragments of rock as large as towers."

In Chap. III., sections 19-21, we find this account:

"Duris informs us that the Rhagæ in Media gained that appellation from chasms made in the ground near the Gates of the Caspian by earthquakes, in which many cities and villages were destroyed, and the rivers underwent various changes. Ion, in his satirical composition of Omphale, has said of Eubœa,

"The light wave of the Euripus has divided the land of Eubœa from Bœotia, separating the projecting land by a strait."

"20. Demetrius of Callatis, speaking of the earthquakes which formerly occurred throughout the whole of Greece, states that a great portion of the Lichadian Islands and of Kenæum were submerged; that the hot springs of Ædepsus and Thermopylæ were suppressed for three days, and that when they commenced to run again those of Ædepsus gushed from new fountains. That at Oreus on the sea coast the wall and nearly seven hundred houses fell at once. That the greater part of Echinus, Phalara, and Heraclæa of Trachis were thrown down, Phalara being overturned from its very foundations. That almost the same misfortune occurred to the Lamians and inhabitants of Larissa; that Scarpheia was overthrown from its foundations, not less than one thousand seven hundred persons being swallowed up, and at Thronium more than half that number. That a torrent of water gushed forth taking three directions, one to Scarphe and Thronium, another to Thermopylæ, and a third to the plains of Daphnus in Phocis. That the springs of (many) rivers were for several days dried up; that the course of the Sperchius was changed, thus rendering navigable what formerly was highways; that the Boagrius flowed through another channel; that many parts of Alope, Cynus and Opus were injured, and the castle of Cœum, which commands the latter city, entirely overturned. That part of the wall of Elateia was thrown down; and that at Alponus, during the celebration of the

games in honour of Ceres, twenty-five maidens, who had mounted a tower to enjoy the show exhibited in the port, were precipitated into the sea by the falling of the tower. They also record that a large fissure was made (by the water) through the midst of the island of Atalanta, opposite Eubœa, sufficient for ships to sail in; that the course of the channel was in places as broad as twenty stadia between the plains; and that a trireme being raised (thereby) out of the docks, was carried over the walls."

Strabo's description of Vesuvius is of interest:

"Above these places is Mount Vesuvius, which is covered with very beautiful fields, excepting its summit, a great part of which is level, but wholly sterile. It appears ash-coloured to the eye, cavernous hollows appear formed of blackened stones, looking as if they had been subjected to the action of fire. From this we may infer that the place was formerly in a burning state with live craters, which however became extinguished on the failing of the fuel. Perhaps this (volcano) may have been the cause of the fertility of the surrounding country, the same as occurs in Catana, where they say that that portion which has been covered with ashes thrown up by the fires of Ætna is most excellent for the vine." (Lib. V., Cap. 4, § 8; p. 367 in vol. I of Bohn's Transl.).

Again in Lib. V., Cap. 4, § 9, he continues:

"In front of Misenum lies the island of Prochyta, which has been rent from the Pithecussæ. Pithecussæ was peopled by a colony of Eretrians and Chalcidians, which was very prosperous on account of the fertility of the soil and the productive gold-mines; however, they abandoned the island on account of civil dissensions, and were ultimately driven out by earthquakes, and eruptions of fire, sea, and hot waters. It was on account of these eruptions, to which the island is subject, that the colonists sent by Hiero, the king of Syracuse, abandoned the island, together with the town which they had built, when it was taken possession of by the Neapolitans. This explains the myth concerning Typhon, who, they say, lies beneath the island, and when he turns himself, causes flames and water to rush forth, and sometimes even small islands to rise in the sea, containing springs of hot water. Pindar throws more credibility into the myth, by making it conformable to the actual phenomena, for the whole strait from Cumæa to Sicily is subigneous, and below the sea has certain galleries which form a communication between (the volcanoes of the island) and those of the main-land. He shows that Ætna is on this account of the nature described by all, and also the Lipari Islands, with the regions around Dicæarchia, Neapolis, Baiæ, and the Pithecussæ. And mindful hereof, (Pindar) says that Typhon lies under the whole of the space.

"Now indeed the sea-girt shores beyond Cumæ, and Sicily, press on his shaggy breast."

"Timæus, who remarks that many paradoxical accounts were related by the ancients concerning the Pithecussæ, states, nevertheless, that a little before his time, Mount Epomeus, in the middle of the island, being shaken by an earthquake, vomited forth fire; and that the land between it and the coast was driven out into the sea. The powdered soil, after being whirled

high, was poured down again upon the island in a whirlwind. That the sea retired from it to a distance of three stadia, but after remaining so for a short time it returned, and inundated the island, thus extinguishing the fire. And the inhabitants of the continent fled at the noise, from the sea-coast, into the interior of Campania."

The following passage about the town of the Rhegini gives Strabo's views of volcanoes as safety valves (Lib. VI., Cap. I, § 6, pp. 386-387) :

"It was called Rhegium either, as Aeschylus says, because of the convulsions which had taken place in this region; for Sicily was broken from the continent by earthquakes,

" ' Whence it is called Rhegium.' "

Others, as well as he, have affirmed the same thing, and adduce as an evidence that which is observed about Ætna, and the appearances seen in other parts of Sicily, the Lipari and neighbouring islands, and even in the Pithecussæ, with the whole coast beyond them, which prove that it was not unlikely that this convulsion had taken place. But now these mouths being opened, through which fire is drawn up, and the ardent masses and water poured out, they say that the land in the neighbourhood of the Strait of Sicily rarely suffers from the effects of earthquakes; but formerly all the passages to the surface being blocked up, the fire which was smouldering beneath the earth, together with the vapour, occasioned terrible earthquakes, and the regions, being disturbed by the force of the pent up winds, sometimes gave way, and being rent received the sea, which flowed in from either side; and thus were formed both this strait and the sea which surrounds the other islands in the neighbourhood. For Prochyta and the Pithecussæ, as well as Capræ, Leucosia, the Sirenes, and the Cænotrides, are but so many detached fragments from the continent, but other islands have risen from the bottom of the sea, a circumstance which frequently occurs in many places; for it is more reasonable to think that the islands in the midst of the sea have been raised up from the bottom, and that those which lie off headlands and are separated merely by a strait were broken off from them."

In describing Mount Aetna he says (Lib. VI., Cap. 2, § 8-9; pp. 414-415) :

"Near to Centoripa is the town we have a little before mentioned, Ætna, which serves as a place for travelers about to ascend Mount Ætna, to halt and refresh themselves for the expedition. For here commences the region in which is situated the summit of the mountain. The districts above are barren and covered with ashes, which are surmounted by the snows in winter; all below it however is filled with woods and plantations of all kinds. It seems that the summits of the mountain take many changes by the ravages of the fire, which sometimes is brought into one crater, and at another is divided; at one time again it heaves forth streams of lava, and at another flames and thick smoke: at other times again ejecting red-hot masses of fire-stone. In such violent commotions as these the subterranean passages

must necessarily undergo a corresponding change, and at times the orifices on the surface around be considerably increased. Some who have very recently ascended the mountain, reported to us, that they found at the top an even plain of about 20 stadia in circumference, enclosed by an overhanging ridge of ashes about the height of a wall, so that those who are desirous of proceeding further are obliged to leap down into the plain. They noticed in the midst of it a mound; it was ash-coloured, as was likewise the plain in appearance. Above the mound a column of cloud reared itself in a perpendicular line to the height of 200 stadia, and remained motionless (there being no air stirring at the time); it resembled smoke. Two of the party resolutely attempted to proceed further across this plain, but, finding the sand very hot and sinking very deep in it, they turned back, without however being able to make any more particular observations, as to what we have described, than those who beheld from a greater distance. They were, however, of opinion, from the observations they were able to make, that much exaggeration pervades the accounts we have of the volcano, and especially the tale about Empedocles, that he leaped into the crater, and left as a vestige of his folly one of the brazen sandals which he wore, it being found outside at a short distance from the lip of the crater, with the appearance of having been cast up by the violence of the flame; for neither is the place approachable nor even visible, nor yet was it likely that anything could be cast in thither, on account of the contrary currents of vapours and other matters cast up from the lower parts of the mountain, and also on account of the overpowering excess of heat, which would most likely meet any one before approaching the mouth of the crater; and if eventually any thing should be cast down, it would be totally decomposed before it were cast up again, what manner of form soever it might have had at first. And again, although it is not unreasonable to suppose that the force of the vapour and fire is occasionally slackened for want of a continual supply of fuel, still we are not to conclude that it is ever possible for a man to approach it in the presence of so great an opposing power. *Ætna* more especially commands the shore along the Strait and Catana, but it also overlooks the sea that washes Tyrrhenia and the Lipari Islands. By night a glowing light appears on its summit, but in the day-time it is enveloped with smoke and thick darkness.

"The Nebrodes mountains take their rise opposite to *Ætna*; they are not so lofty as *Ætna*, but extend over a much greater surface. The whole island is hollow under ground, and full of rivers and fire like the bed of the Tyrrhenian Sea, as far as Cumæa, as we before described. For there are hot springs in many places in the island, some of which are saline, as those named Selinuntia and the springs at Himera, while those at *Ægesta* are fresh."

Again (Lib. VI., cap. 2, § 10; pp. 417-418) Strabo says:

"Phænomena, similar to these, and such as take place throughout Sicily, are witnessed in the Lipari Islands, and especially in Lipari itself. These islands are seven in number, the chief of which is Lipari, a colony of the Cnidians. It was nearest to Sicily after Thermessa. It was originally named

Meligunis. It was possessed of a fleet, and for a considerable time repelled the incursions of the Tyrrheni. The islands now called Liparæan were subject to it, some call them the islands of Æolus. The citizens were so successful as to make frequent offerings of the spoils taken in war to the temple of Apollo at Delphi. It possesses a fertile soil, and mines of alum easy to be wrought, hot springs, and craters. (Thermessa) is, as it were, situated between this and Sicily; it is now designated as Hiera, or sacred to Vulcan; it is entirely rocky, and desert, and volcanic. In it are three craters, and the flames which issue from the largest are accompanied with burning masses of lava, which have already obstructed a considerable portion of the strait (between Thermessa and the island Lipari); repeated observations have led to the belief that the flames of the volcanoes, both in this island and at Mont Ætna, are stimulated by the winds as they rise; and when the winds are lulled, the flames also subside; nor is this without reason, for if the winds are both originally produced and kept up by the vapours arising from the sea, those who witness these phenomena will not be surprised, if the fire should be excited in some such way, by the like aliment and circumstances. Polybius tells us that one of the three craters of the island has partly fallen down, while the larger of the two that remain has a lip, the circumference of which is five stadia, and the diameter nearly fifty feet, and its elevation about a stadium from the level of the sea, which may be seen at the base in calm weather; but if we are to credit this, we may as well attend to what has been reported concerning Empedocles. (Polybius) also says, that when the south wind is to blow, a thick cloud lies stretched round the island, so that one cannot see even as far as Sicily in the distance; but when there is to be a north wind, the clear flames ascend to a great height above the said crater, and great rumblings are heard; while for the west wind effects are produced about half way between these two. The other craters are similarly affected, but their exhalations are not so violent. Indeed, it is possible to foretell what wind will blow three days beforehand, from the degree of intensity of the rumbling, and also from the part whence the exhalations, flames, and smoky blazes issue."

Strabo describes the Aeloian Islands, and includes this account of one of them (Lib. VI., cap. 2, § 11; pp. 420-421):

"The seventh (island) is called Euonymus; it is the farthest in the sea and barren. It is called Euonymus because it lies the most to the left when you sail from the island of Lipari to Sicily, and many times flames of fire have been seen to rise to the surface, and play upon the sea round the islands: these flames rush with violence from the cavities at the bottom of the sea, and force for themselves a passage to the open air. Posodinius says, that at a time so recent as to be almost within his recollection, about the summer solstice and at break of day, between Hiera and Euonymus, the sea was observed to be suddenly raised aloft, and to abide sometime raised in a compact mass and then to subside. Some ventured to approach that part in their ships; they observed the dead fish driven by the current, and being distressed by the heat and foul smell, were compelled to turn back. One of the boats which approached the nearest lost some of her crew,

and was scarcely able to reach Lipari with the rest, and they had fits like an epileptic person, at one time fainting and giddy, and at another returning to their senses; and many days afterwards a mud or clay was observed rising in the sea, and in many parts the flames issued, and smoke and smoky blazes; afterwards it congealed and became a rock like mill-stones. Titus Flaminus, who then commanded in Sicily, despatched to the senate (of Rome) a full account of the phenomenon; the senate sent and offered sacrifices to the infernal and marine divinities both in the little island (which had thus been formed) and the Lipari Islands."

Strabo mentions (Book viii., Chap. vi., § 19, Vol. II., p. 59) the cities enumerated in Homer's Catalogue of Ships (*Illiad*, ii., 569) including "spacious Helice" (*Ἑλικὴν εὐρείαν*). In Book viii., Chap. vii., § 2; pp. 69-70, he recounts the development of Achaian power, and say they began in the time of Pyrrhus with four cities:

"They then had an accession of the twelve cities, with the exception of Olenus and Helice; the former refused to join the league; the other was swallowed up by the waves.

"For the sea was raised to a great height by an earthquake, and overwhelmed both Helice and the temple of the Heliconian Neptune, whom the Ionians still hold in great veneration, and offer sacrifices to his honour. They celebrate at that spot the Panionian festival. According to the conjecture of some persons, Homer refers to these sacrifices in these lines,

"'But he breathed out his soul, and bellowed, as a bull

Bellows when he is dragged round the altar of the Heliconian king.'

"It is conjectured that the age of the poet is later than the migration of the Ionian colony, because he mentions the Panionian sacrifices, which the Ionians perform in honour of the Heliconian Neptune in the territory of Priene; for the Prienians themselves are said to have come from Helice; a young man also of Priene is appointed to preside as king at these sacrifices, and to superintend the celebration of the sacred rites. A still stronger proof is adduced from what is said by the poet respecting the bull, for the Ionians suppose, that sacrifice is performed with favorable omen, when the bull bellows at the instant that he is wounded at the altar.

"Others deny this, and transfer to Helice the proofs alleged of the bull and the sacrifice, asserting that these things were done there by established custom, and that the poet drew his comparison from the festival celebrated there. Helice was overwhelmed by the waves two years before the battle of Leuctra. Eratosthenes says, that he himself saw the place, and the ferry-men told him that there formerly stood in the strait a brazen statue of Neptune, holding in his hand a hippocampus, an animal which is dangerous to fishermen.

"According to Heracleides, the inundation took place in his time, and during the night. The city was at the distance of twelve stadia from the sea, which overwhelmed the whole intermediate country as well as the city. Two thousand men were sent by the Achæans to collect the dead bodies, but in vain. The territory was divided among the bordering people. This

calamity happened in consequence of the anger of Neptune, for the Ionians, who were driven from Helice, sent particularly to request the people of Helice to give them the image of Neptune, or if they were unwilling to give that, to furnish them with the model of the temple. On their refusal, the Ionians sent to the Achæan body, who decreed, that they should comply with the request, but they would not obey even this injunction. The disaster occurred in the following winter, and after this the Achæans gave the Ionians the model of the temple."

§ 21. *The Theory of Pliny (23-79 A.D.).*

The following extracts are taken from Bohn's excellent translation of the "Natural History." They exhibit the views of Pliny, who follows closely the theory of Aristotle.

In Book II., of the Natural History, will be found Pliny's account of earthquakes, which runs thus :

"CHAP. 81 (79)—OF EARTHQUAKES.

"According to the doctrine of the Babylonians,¹ earthquakes and clefts of the earth, and occurrences of this kind, are supposed to be produced by the influence of the stars, especially of the three to which they ascribe thunder (Saturn, Jupiter and Mars); and to be caused by the stars moving with the sun, or being in conjunction with it, and, more particularly, when they are in the quartile aspect. If we are to credit the report, a most admirable and immortal spirit, as it were of a divine nature, should be ascribed to Anaximander the Milesian, who, they say, warned the Lacedæmonians to beware of their city and their houses. For he predicted that an earthquake was at hand, when both the whole of their city was destroyed and a large portion of Mount Taygetus, which projected in the form of a ship, was broken off, and added farther ruin to the previous destruction. Another prediction is ascribed to Pherecydes, the master of Pythagoras, and this was divine; by a draught of water from a well, he foresaw and predicted that there would be an earthquake in that place. And if these things be true, how nearly do these individuals approach to the Diety, even during their lifetime! But I leave every one to judge of these matters as he pleases. I certainly conceive the winds to be the cause of earthquakes; for the earth never trembles except when the sea is quite calm, and when the heavens are so tranquil that the birds cannot maintain their flight, all the air which should support them being withdrawn; nor does it ever happen until after great winds, the gust being pent up, as it were, in the fissures and concealed hollows. For the trembling of the earth resembles thunder in the clouds; nor does the yawning of the earth differ from the bursting of the lightning; the enclosed air struggling and striving to escape.

"CHAP. 82 (80)—OF CLEFTS OF THE EARTH.

"The earth is shaken in various ways, and wonderful effects are produced; in one place the walls of cities being thrown down, and in others swallowed up by a deep cleft; sometimes great masses of earth are heaped

¹ Pliny here refers to the Astrologers, who were said to have come originally from Babylon.

up, and rivers forced out, sometimes even flame and hot springs, and at others the course of rivers is turned. A terrible noise precedes and accompanies the shock; sometimes a murmuring, like the lowing of cattle, or like human voices, or the clashing of arms. This depends on the substance which receives the sound, and the shape of the caverns or crevices through which it issues; it being more shrill from a narrow opening, more hoarse from one that is curved, producing a loud reverberation from hard bodies, a sound like a boiling fluid from moist substances, fluctuating in stagnant water, and roaring when forced against solid bodies. There is, therefore, often the sound without any motion. Nor is it a simple motion, but one that is tremulous and vibratory. The cleft sometimes remains, displaying what it has swallowed up; sometimes concealing it, the mouth being closed and the soil being brought over it, so that no vestige is left; the city being, as it were, devoured, and the tract of country engulfed. Maritime districts are more especially subject to shocks. Nor are mountainous tracts exempt from them; I have found, by my inquiries, that the Alps and the Apennines are frequently shaken. The shocks happen more frequently in the autumn and in the spring, as is the case also with thunder. There are seldom shocks in Gaul and in Egypt; in the latter it depends on the prevalence of summer, in the former of winter. They also happen more frequently in the night than in the day. The greatest shocks are in the morning and the evening; but they often take place at daybreak, and sometimes at noon. They also take place during the eclipses of the sun and of the moon, because at that time storms are lulled. They are most frequent when great heat succeeds to showers, or showers succeed to great heat.

“CHAP. 83 (81)—SIGNS OF AN APPROACHING EARTHQUAKE.

“There is no doubt that earthquakes are felt by persons on shipboard, as they are struck by a sudden motion of the waves, without these being raised by any gust of wind. And things that are in the vessels shake as they do in houses, and give notice by their creaking; also the birds, when they settle upon the vessels, are not without their alarms. There is also a sign in the heavens; for, when a shock is near at hand, either in the daytime or a little after sunset, a cloud is stretched out in the clear sky, like a long thin line. The water in wells is also more turbid than usual, and it emits a disagreeable odour.

“CHAP. 84 (82)—PRESERVATIVES AGAINST FUTURE EARTHQUAKES.

“These same places, however, afford protection, and this is also the case where there is a number of caverns, for they give vent to the confined vapour, a circumstance which has been remarked in certain towns, which have been less shaken where they have been excavated by many sewers. And, in the same town, those parts that are excavated are safer than the other parts, as is understood to be the case at Naples in Italy, the part of which is solid being more liable to injury. Arched buildings are also the most safe, also the angles of walls, the shocks counteracting each other; walls made of brick also suffer less from the shocks. There is also a great difference in the nature of the motions, where various motions are experienced.

It is safest when it vibrates and causes a creaking in the building, and where it swells and rises upwards, and settles with an alternate motion. It is also harmless when the buildings coming together butt against each other in opposite directions, for the motions counteract each other. A movement like the rolling of waves is dangerous, or when the motion is impelled in one direction. The tremors cease when the vapour bursts out; but if they do not soon cease, they continue for forty days; generally, indeed, for a longer time: some have lasted even for one or two years.

"CHAP. 85 (83)—PRODIGIES OF THE EARTH WHICH HAVE OCCURRED ONCE ONLY.

"A great prodigy of the earth, which never happened more than once, I have mentioned in the books of the Etruscan ceremonies, as having taken place in the district of Mutina, during the consulship of Lucius Martius and Sextus Julius. Two mountains rushed together, falling upon each other with a very loud crash, and then receding; while in the daytime flame and smoke issued from them; a great crowd of Roman knights, and families of people, and travellers on the Æmilian way, being spectators of it. All the farm-houses were thrown down by the shock, and a great number of animals that were in them were killed; it was in the year before the Social war; and I am in doubt whether this event or the civil commotions were more fatal to the territory of Italy. The prodigy which happened in our own age was no less wonderful; in the last year of the emperor Nero, as I have related in my history of his times, when certain fields and olive grounds in the district of Marrucinum, belonging to Vectius Marcellus, a Roman knight, the steward of Nero, changed places with each other, although the public highway was interposed.

"CHAP. 86 (84)—WONDERFUL CIRCUMSTANCES ATTENDING EARTHQUAKES.

"Inundations of the sea take place at the same time with earthquakes; the water being impregnated with the same spirit, and received into the bosom of the earth which subsides. The greatest earthquake which has occurred in our memory was in the reign of Tiberius, by which twelve cities of Asia were laid prostrate in one night. They occurred the most frequently during the Punic war, when we had accounts brought to Rome of fifty-seven earthquakes in the space of a single year. It was during this year that the Carthaginians and the Romans, who were fighting at the lake Thrasimenus, were neither of them sensible of a very great shock during the battle. Nor is it an evil merely consisting in the danger which is produced by the motion; it is an equal or a greater evil when it is considered as a prodigy. The city of Rome never experienced a shock, which was not the forerunner of some great calamity.

"CHAP. 87 (85)—IN WHAT PLACE THE SEA HAS RECEDED.

"The same cause produces an increase of the land; the vapour, when it cannot burst out forcibly lifting up the surface. For the land is not merely produced by what is brought down the rivers, as the islands called Echinades are formed by the river Achelous, and the greater part of Egypt by the Nile, where, according to Homer, it was a day and a night's journey from

the mainland to the island of Pharos; but in some cases, by the receding of the sea, as, according to the same author, was the case with the Circæan isles. The same thing also happened in the harbour of Ambracia, for a space of 10,000 paces, and was also said to have taken place for 5000 at the Piræus of Athens, and likewise at Ephesus, where formerly the sea washed the walls of the temple of Diana. Indeed, if we may believe Herodotus, the sea came beyond Memphis, as far as the mountains of Æthiopia, and also from the plains of Arabia. The sea also surrounded Ilium and the whole of Teuthrania, and covered the plain through which the Mæander flows.

CHAP. 88 (86)—THE MODE IN WHICH ISLANDS RISE UP.

"Land is sometimes formed in a different manner, rising suddenly out of the sea, as if nature was compensating the earth for its losses, restoring in one place what she had swallowed up in another.

"CHAP. 89 (87)—WHAT ISLANDS HAVE BEEN FORMED, AND AT WHAT PERIODS.

"Delos and Rhodes, islands which have now been long famous, are recorded to have risen up in this way. More lately there have been some smaller islands formed; Anapha, which is beyond Melos; Nea, between Lemnos and the Hellespont; Halone, between Lebedos and Teos; Thera and Therasia, among the Cyclades, in the fourth year of the 135th Olympiad. And among the same islands, 130 years afterwards, Hiera, also called Automate, made its appearance; also Thia, at the distance of two stadia from the former, 110 years afterwards, in our own times, when M. Junius Silanus and L. Balbus were consuls, on the 8th of the ides of July.

"88. Opposite to us, and near to Italy, among the Æolian isles, an island emerged from the sea; and likewise one near Crete, 2,500 paces in extent, and with warm springs in it; another made its appearance in the third year of the 163rd Olympiad, in the Tuscan gulf, burning with a violent explosion. There is a tradition too that a great number of fishes were floating about the spot, and that those who employed them for food immediately expired. It is said that the Pithecusan isles rose up, in the same way, in the bay of Campania, and that shortly afterwards, the mountain Epopos, from which flame had suddenly burst forth, was reduced to the level of the neighbouring plain. In the same island, it is said, that a town was sunk in the sea; that in consequence of another shock, a lake burst out, and that, by a third, Prochyta was formed into an island, the neighbouring mountains being rolled away from it.

"CHAP. 90—LANDS WHICH HAVE BEEN SEPARATED BY THE SEA.

"In the ordinary course of things islands are also formed by this means. The sea has torn Sicily from Italy, Cyprus from Syria, Eubœa from Bœotia. Atalante and Macris from Eubœa, Besbycus from Bithynia, and Leucosia from the promontory of the Sirens.

"CHAP. 91 (89)—ISLANDS WHICH HAVE BEEN UNITED TO THE MAINLAND.

"Again, islands are taken from the sea and added to the mainland; Antissa to Lesbos, Zephyrium to Halicarnassus, Æthusa to Myndus, Dro-

miscus and Perne to Miletus, Narthecusa to the promontory of Parthenium. Hybanda, which was formerly an island of Ionia, is now 200 stadia distant from the sea. Syries is now become a part of Ephesus, and, in the same neighborhood, Derasidas and Sophonia form part of Magnesia; while Epidaurus and Oricum are no longer islands.

"CHAP. 92 (90)—LANDS WHICH HAVE BEEN TOTALLY CHANGED INTO SEAS.

"The sea has totally carried off certain lands, and first of all, if we are to believe Plato, for an immense space where the Atlantic ocean is now extended. More lately we see what has been produced by our inland sea; Acarnania has been overwhelmed by the Ambracian gulf, Achaia by the Corinthian, Europe and Asia by the Propontis and Pontus. And besides these, the sea has rent asunder Leucas, Antirrhium, the Hellespont, and the two Bosphori.

"CHAP. 93 (91)—LANDS WHICH HAVE BEEN SWALLOWED UP.

"And not to speak of bays and gulfs, the earth feeds on itself; it has devoured the very high mountain of Cybotus, with the town of Curites; also Sipylus in Magnesia, and formerly, in the same place, a very celebrated city, which was called Tantalus; also the land belonging to the cities Galanis and Gamales in Phœnicia, together with the cities themselves; also Phegium, the most lofty ridge in Æthiopia. Nor are the shores of the sea more to be depended upon.

"CHAP. 94 (92)—CITIES WHICH HAVE BEEN ABSORBED BY THE SEA.

"The sea near the Palus Mæotis has carried away Pyrrha and Antissa, also Elice and Bura in the gulf of Corinth, traces of which places are visible in the ocean. From the island Cea it has seized on 30,000 paces, which were suddenly torn off, with many persons on them. In Sicily also the half of the city of Tyndaris, and all the part of Italy which is wanting; in like manner it carried off Eleusina in Bœotia.

Again:

"CHAP. 110 (106)—PLACES WHICH ARE ALWAYS BURNING.

"Among the wonders of mountains there is Ætna, which always burns in the night, and for so long a period has always had materials for combustion, being in the winter buried in snow, and having the ashes which it has ejected covered with frost. Nor is it in this mountain alone that nature rages, threatening to consume the earth; in Phaselis, the mountain Chimæra burns, and indeed with a continual flame, day and night. Ctesias of Cnidos informs us, that this fire is kindled by water, while it is extinguished by earth and by hay. In the same country of Lycia, the mountains of Hephæstius, when touched with a flaming torch, burn so violently, that even the stones in the river and the sand burn, while actually in the water; this fire is also increased by rain. If a person makes furrows in the ground with a stick which has been kindled at this fire, it is said that a stream of flame will follow it. The summit of Cophantus, in Bactria, burns during the night and this is the case in Media and at Sittacene, on the borders of Persia;

likewise in Susa, at the White Tower, from fifteen apertures, the greatest of which also burns in the daytime. The plain of Babylon throws up flame from a place like a fish-pond, an acre in extent. Near Hesperium, a mountain of the Æthiopians, the fields shine in the night-time like stars; the same thing takes place in the territory of the Megalopolitani. This fire, however, is internal, mild, and not burning the foliage of a dense wood which is over it. There is also the crater of Nymphæum, which is always burning, in the neighbourhood of a cold fountain, and which, according to Theopompus, presages direful calamities to the inhabitants of Apollonia. It is increased by rain, and it throws out bitumen, which, becoming mixed with the fountain, renders it unfit to be tasted; it is, at other times, the weakest of all the bitumens. But what are these compared to other wonders? Hiera, one of the Æolian isles, in the middle of the sea, near Italy, together with the sea itself, during the Social war, burned for several days, until expiation was made, by a deputation from the senate. There is a hill in Æthiopia called *Θεῶν ὄχημα*, which burns with the greatest violence, throwing out flame that consumes everything, like the sun. In so many places, and with so many fires, does nature burn the earth!"

"CHAP. III (107)—WONDERS OF FIRE ALONE.

"But since this one element is of so prolific a nature as to produce itself, and to increase from the smallest spark, what must we suppose will be the effect of all those funeral piles of the earth? What must be the nature of that thing, which, in all parts of the world, supplies this most greedy voracity without destroying itself? To these fires must be added those innumerable stars and the great sun itself. There are also the fires made by men, those which are innate in certain kinds of stone, those produced by the friction of wood, and those in the clouds, which give rise to lightning. It really exceeds all other wonders, that one single day should pass in which everything is not consumed, especially when we reflect that concave mirrors placed opposite to the sun's rays produce a flame more readily than any other kind of fire; and that numerous small but natural fires abound everywhere. In Nymphæum there issues from a rock a fire which is kindled by rain; it also issues from the waters of the Scantia. This indeed is a feeble flame, since it passes off, remaining only a short time on any body to which it is applied: an ash tree, which overshadows this fiery spring, remains always green. In the territory of Mutina fire issues from the ground on the days that are consecrated to Vulcan. It is stated by some authors, that if a burning body falls on the fields below Aricia, the ground is set on fire; and that the stones in the territory of the Sabines and of the Sidicini, if they be oiled, burn with flame. In Egnatia, a town of Salentinum, there is a sacred stone upon which, when wood is placed, flame immediately bursts forth. In the altar of Juno Lacinia, which is in the open air, the ashes remain unmoved, although the winds may be blowing from all quarters.

"It appears also that there are sudden fires both in waters and even in the human body; that the whole Lake Thrasymenus was on fire; that when Servius Tullius, while a child, was sleeping flame darted out from his head; and Valerius Antias informs us, that the same flame appeared about L.

Marcus, when he was pronouncing the funeral oration over the Scipios, who were killed in Spain; and exhorting the soldiers to avenge their death. I shall presently mention more facts of this nature, and in a more distinct manner; in this place these wonders are mixed up with other subjects. But my mind, having carried me beyond the mere interpretation of nature, is anxious to lead, as it were by the hand, the thoughts of my readers over the whole globe."

In Book III., Chapter 14, Pliny discusses the volcanoes in the Æolian Islands. Book iv., Chapter 6, contains an account of Achaia, in which Pliny mentions the destruction of Helike and Bura, and the towns in which the people who escaped the inundation of the sea afterwards took refuge. After enumerating the cities of Achaia he adds:

"Throughout the whole of this region, as though nature had been desirous to compensate for the inroads of the sea, seventy-six mountains raise their lofty heads." (Book iv., Chap. 10.)

Pliny has the following remarks on the island of Delos (Lib. IV., Chap. 22, pp. 318-319):

"This island long floated on the waves, and, as tradition says, was the only one that had never experienced an earthquake, down to the time of M. Varro; Mucianus however has informed us, that it has been twice so visited. Aristotle states that this island received its name from the fact of its having so suddenly made its appearance on emerging from the sea; Aglaosthenes, however, gives it the name of Cynthia, and others of Ortygia, Asteria, Lagia, Chlamydia, Cynthus, and from the circumstance of fire having been first discovered here, Pyrpile. Its circumference is five miles only; Mount Cynthus here raises his head."

The reader will see from these accounts that Pliny follows Aristotle and Strabo. They all hold that earthquakes are due to the efforts of elastic vapors to escape through the ground and diffuse themselves in the atmosphere. In Chapter 82 (80), Book II., Pliny remarks: "Maritime districts are more especially subject to shocks." Whether this is an independent observation, or he merely followed the sagacious remarks of Aristotle, whose remarkable theory we have translated in section 19, the statement is equally interesting and true.

If then earthquakes are especially frequent in maritime districts, and are due to efforts of elastic vapors seeking to diffuse themselves in the atmosphere, may it not be justly said that although they did not have a satisfactory explanation of the penetration of the vapors into the earth, the leading philosophers of Greece and

Rome came very near the true theory of earthquakes as we conceive it to-day?

V. ON THE ANCIENT AND MODERN THEORY OF EARTHQUAKES,
ON THE SINKING OF HELIKE, AND ON THE MOVEMENTS
TAKING PLACE IN THE ÆGEAN AND ASIA MINOR.

§ 22. *Common Views of Plato, Aristotle, Strabo and Pliny.*

From the accounts quoted in the foregoing extracts, we have seen that Plato held that air and water, entering through hollows and crevices, obtained access to the bowels of the earth, and that there are everywhere beneath the earth rivers and lakes of fire (Pyriphlegethon), some of which he had seen emitted from Mt. Ætna. Owing to his pictorial style of exposition Plato's accounts are more or less allegorical, but these general results seem sufficiently clear to be beyond doubt. Aristotle was trained under Plato, but he afterwards departed from the style of composition employed in the Academy, and adopted in all his mature writings the modern scientific method of simple direct statement of facts.

Accordingly in the writings of Aristotle we see the theory of earthquakes as taught by the master mind during the culmination of the physical philosophy of the Greeks. Aristotle was not only the greatest natural philosopher of Greece, but of antiquity, and one of the most luminous intellects of all time. No other mind of any age or country has exerted so great an influence on scientific thought or on its terminology. Thus Eusebius designates him as "Nature's private Secretary," while Dante calls him the "master of those who know," in reference no doubt especially to his development of the methods of logic. But Aristotle's genius extended to every branch of human knowledge, and ornamented everything it touched.

In spite of some errors, incident to the early age in which he lived, his observations of nature show the highest order of sagacity and mental penetration, and will always give him the foremost place among the philosophers of antiquity. In his mental activity he felt the necessity for physical laws, and thus became accustomed to seek the *causes* of things; so that in Strabo we find complaint of his depth of thought. His mind was therefore preëminently scientific in the highest sense of the word, and no modern thinker has surpassed him in subtileness and power of intuition.

Like Plato he recognized water and air as entering into the bowels of the globe, through hollows, caverns and fissures; and there, in contact with the internal heat, giving rise to imprisoned vapor, which develops such force that it brings on an earthquake. He fully recognized the prevalence of earthquakes in maritime regions, and on this point his views have been adopted by Strabo and Pliny.

In the time of Aristotle the universe was conceived as made up of four elements, fire, air, water, and earth. But the Greeks noticed the evaporation of water, and its precipitation from the clouds in the form of rain, hail and snow; and they recognized that there was some process by which it became invisible, and was afterwards condensed into clouds and precipitated by atmospheric agencies. Aristotle does not usually distinguish vapor of steam from air, though occasionally he calls steam *ἀτμός*, while ordinary wind is called *ἄνεμος*. He must have conceived the two vapors as passing by some unknown process one into the other.

Accordingly when he says vapor, air, or wind, we are often to understand not only atmospheric air, but also a mixture of vapor of steam. Since such vapor is seen to be emitted by volcanoes, as in the case he mentions of the Æolian Island Hiera, now called Vulcano, he naturally and correctly reasons that it was the cause of that violent outbreak.¹ In like manner Aristotle holds that vapor is the cause of the agitation of the earth even when no surface eruption occurs. He recognized therefore that the tension of elastic vapor seeking to diffuse itself in the atmosphere may become so powerful as to overcome the confining rocks of the earth's crust, and bring on an earthquake, even though none escapes to the surface, but the whole of it remains hidden in the earth. In this view he is followed by Lucretius, Strabo, and Pliny. How much more

¹ Paulus Orosius (Lib. LV., Cap. 20) says that this island, which was often called Thermessa by the ancients, arose from the sea in the year 571 B.C. A passage in Thucydides (Lib. III., § 88) shows that it was in existence in 427 B.C. (cf. Strabo's Geography, Bohn's Transl., vol. 1, p. 417, footnote). This date of 571 B.C. is consistent with the date given by Aristotle. Pliny's statement (Lib. II., Cap. 89; Vol. 1, p. 118) is incorrect, and may perhaps be explained by a transcriber's error, or by some confusion of Pliny himself. Perhaps Thermessa was confounded with Therasia near Thera.

philosophical and accordant with Newton's rule this is than the singular modern method of dividing earthquakes into two separate classes, volcanic and tectonic!

Aristotle holds not only that earthquakes are due to vapor in the earth, but also that they are most prevalent near the sea. In other parts of the "Meteorology" (Lib. I, Cap. iv.), he says that the "distribution of land and sea in particular regions does not endure throughout all time, but it becomes sea in those parts where it was land, and again it becomes land where it was sea"; and finally adds "everything changes in the course of time." Aristotle also correctly associated seismic sea waves with earthquakes, and points out cases of islands and volcanoes upheaved in the sea. The philosophical position which he occupied was thus extraordinarily advanced, and there is little wonder that his views were adopted and elaborated by Strabo and Pliny. This simple and orderly development of thought among the ancients is in melancholy contrast to the disconnected and anachronous views still prevalent on these subjects in our own time.

§ 23. *Explanation of the Sinking of Helike and destruction of Bura, 373 B.C.*

We have seen that Strabo says that Helike sank in the night,¹ after the region had been shaken by a great earthquake. He says Helike was 12 stadia from the sea, and Bura 40 stadia, about 1.5 and 5 miles respectively. In his large work on the "Face of the Earth" (Vol. II., pp. 448, 464) Professor Suess explains this sinking by the shaking down of an alluvial deposit, which broke loose from the older formation, thus causing it to slip into the sea. The process described by Suess is a familiar one where a narrow band of soil is formed near steep cliffs; but this shaking loose obviously could not occur where the extent of the deposit is from 1.5 to 5 miles in width. No alluvial deposit of this width would slide during an earthquake, unless it was on the slope of a comparatively steep mountain, and the strata under it were inclined at a steep angle, of say 30°, which was not the case in the region of Helike and Bura. These cities were both built on decidedly solid lowlands along the seashore, and with such a broad base the alluvial deposits could not slide into the sea. What J. Schmidt ob-

¹ According to Heracleides.

served in the same region after the earthquake which shook Ægion, December 26, 1861, may possibly have been due to the settlement of the alluvium, but it is much more probable that it arose from a sinking of the crust along the line of a hidden fault, similar to that which so severely rent the ground under Bura in 373 B.C.

It is usually stated that Bura was covered by the sea like Helike, but some of the ancient authors correctly imply that the ruin was mainly due to the opening of fissures of the earth, which caused the houses to be engulfed. Others say that it was also covered by the sea, but both here and at Helike some objects remained above the water. Bura, however, was built on a hill and ruins of it are still extant at considerable elevation above the sea level.

The land which sank when Helike was submerged beneath the waves was evidently similar to that now seen along the southern shore of the gulf of Corinth. A railroad now traverses this shore almost the entire length of the gulf. While on a visit to Delphi early in April, 1891, the writer crossed the gulf in a sail boat, and took the train for Olympia near this ancient site of Helike and Bura. The lay of the land is gentle and nowhere is the ascent other than very gradual. The mountains of Arcadia are quite a distance away, but usually visible to the traveler. From my own observations of the southern shore of the gulf, along the region where Helike now lies beneath the waves, I feel sure that the land of this entire region is too solid to experience appreciable settling under the shaking of an earthquake. What then was the cause of the disaster of 373 B.C.?

In the paper on the cause of earthquakes, we have seen that in world-shaking seismic disturbances lava moves beneath the crust, and usually is expelled from under the bed of the sea. After the crust is thus undermined, the sea bottom frequently subsides, and the sinking of the bed of the sea draws the water away from the shore and causes the seismic sea waves. The gulf of Corinth is a sea trough, with high mountains on both sides; and in 373 B.C. lava was expelled from under it and pushed under the mountains to the north or south—most likely under the Arcadian mountains to the south; and after the lava was expelled the bed of the trough sank down, carrying with it the shores on which Helike stood.

The mountains north of Delphi, including Parnassus and Helicon, as well as those further west in Ætolia, like those to the south in Arcadia, have all been pushed up by the expulsion of lava from beneath the gulf of Corinth. Now the accounts of the destruction of Helike show that the region was first terribly shaken by an earthquake, obviously by the movement of lava streams beneath the crust, what Plato would perhaps call *Pyriphlegethon*, and then inundated by the sea, the town afterwards remaining largely or wholly under water. This can only mean that the bottom of the gulf gave down, and carried the southern shore down with it; perhaps the fault which moved is beneath the deep soil and did not show at the surface, except in the chasms which appeared at Bura, as mentioned by Aristotle. If alluvium of such great age could settle at all under the shaking of an earthquake, the amount of the subsidence could not exceed a very few feet. This was found to be true of the soft land at San Francisco which had been made within a quarter of a century before the great earthquake of April 18, 1906, and the same conclusion is drawn from observations of many other great earthquakes of recent years. Such shaking down would not be adequate to account for the submergence of Helike beneath the waves.

This town could hardly have been less than 50 feet above the sea level of the gulf, and a height of 80 feet is much more probable, owing to the universal custom of the Greeks of building a town always on the highest available point and crowning it with an Acropolis, containing the temples of the gods. The houses would be at least 20 feet high, so that the subsidence must have been at least 70 feet, and it was more probably from 80 to 100 feet. The amount of the subsidence, even if we take the lowest figure, 70 feet, is altogether too great to be accounted for by mere shaking down of alluvium deposited hundreds of thousands of years ago. And the distance from the sea mentioned by Strabo, who could not well be mistaken, shows that a sliding of the whole broad alluvial deposit could not have taken place.

Moreover, the account given by Aristotle, within whose lifetime the event had occurred, implies that the seismic sea wave was of that class in which the water first retires from the shore (*πρώσους*)

and then returns after the currents have met and raised a ridge in the centre of the depression. By no possibility can we interpret Aristotle's account to indicate an elevation of the sea bottom, as when a volcano is upheaved, which would cause the waters to rise suddenly without previous recession from the shore. The only other class of sea waves is that in which the water retires after the earthquake, and Aristotle's language distinctly implies that this recession took place. Moreover, Strabo says that the disaster was attributed to the anger of Poseidon, "the earth-shaker," to whom were ascribed the sea waves accompanying great earthquakes.

If this view be admissible, it will follow that the sinking of Helike was by the usual process of subsidence in seismic sea waves of the first class, except that the subsidence of the bottom of the gulf carried down also part of the shore. As the gulf is quite narrow such a result is probable in the highest degree.

This sinking of the shore along the bed of the sea is not unusual even where the sea is wide; but for the sake of convenience of diction we have ordinarily spoken only of the sinking of the sea bottom rather than of the land along the shore. Unless there is movement of a fault with vertical walls, the change of level is naturally gradual, depending on the yielding and flexure of the earth's crust when lava is injected or expelled from beneath it.

§ 24. *Further Considerations on the Elevation of the Himalayas, Based on the Relief of the Indian Ocean at its Margins.*

In the paper on the cause of earthquakes we have explained the Himalayas by the expulsion of lava from beneath the Indian Ocean, and have attributed the continuance of earthquakes in that region to the activity of the ancient sea trough where the Ganges and Bramaputra now flow. The process there is similar to that found in the Andes, but the mountains are now somewhat further from the sea. In calling attention to the surface leakage in the region south of the Himalayas, there was no thought of implying that the effect of the ocean has ceased; on the contrary there can be no doubt that strain beneath the Indian Ocean's crust is still relieved by the same movements which originally formed and are still raising the Himalaya mountains. The surface waters augment the effects of the relief of strain from beneath the sea, and these two

causes together produce the observed earthquakes. This explains the occurrence of a large earthquake belt south of the Himalayas, the existence of which heretofore has been so perplexing. Where the crust is badly broken and fissured, the surface water more readily aids the original tendency to relief, depending on the secular leakage of the adjacent ocean. We have treated this question in section 20 of the paper on the cause of earthquakes, but the Himalayas were not treated in great detail, and it seemed well to point out specifically that the same tendency to relief, which we find around the margins of the Pacific, holds equally true in the great western extension known as the Indian Ocean. Here at present relief is obtained chiefly along the northern and northeastern borders, though some is afforded in islands and various other places. The Indian Ocean not only has high mountains on its margins, but also a considerable number of islands and volcanoes. In this respect it resembles the Pacific.

A study of the principal mountain chains suggests that whenever a serious break has once occurred in the crust of the earth, the strain arising in the underlying layer continues to find relief by the escape of steam-saturated lava into the avenue thus opened, which is the path of least resistance. The formation of the Alps, Andes and other mountains, as well as the Himalayas, illustrate this principle.

Whether the motion of lava towards the avenue of escape is by creeping flow, or by small earthquakes, we do not know; possibly it may be by both methods. It is only in violent world-shaking earthquakes that we can be sure that lava is moved beneath the crust *en mass* over considerable distances. These streams of lava are proved to exist by the uplift of coasts and by the sinking of the sea bottom implied in seismic sea waves.

Such subterranean movements correspond closely to Plato's Pyriphlegethon, but when once a fault has moved for a long time upward, the strain may become so great from the way in which the blocks of the earth's crust are wedged together, that the upward movement there becomes more difficult, and a neighboring region affords easier relief. And in pushing up the neighboring area, the previously elevated block may be let down again, by the relief

thereby afforded beneath. Thus a mountain system such as the Himalayas, Alps or Andes represents a vast number of such elevations and depressions, and this is the way in which such movements are to be explained. A theory which is capable of furnishing such a simple explanation of such complex phenomena should have a strong claim to acceptance.

The principal escapes from the Indian Ocean seem to be chiefly under the mouths of the Ganges and Indus, and hence we see why these regions are so often disturbed by violent earthquakes. It is noticeable that few important changes of level have been produced there, except subsidence, because these troughs were arched downward, and the surface movement therefore usually has been small.

Some geologists have inferred that earthquakes are common in the deltas of all great rivers. But observation shows that this is not universally, nor even commonly, true. The deltas of the Mississippi and Amazon, so far as known, have never experienced severe earthquakes, and if deposits of sediment were the cause they ought to have felt disturbances like those which have been frequent in the deltas of the Ganges and Indus. But there is an important difference between the Ganges and the Indus, on the one hand, and the Mississippi and Amazon on the other. Under the former are avenues of escape for the steam-saturated lava forming under the Indian Ocean, while little if any escape takes place at the mouth of the Mississippi and Amazon. The Gulf of Mexico is only moderately deep and the crust broken and faulted chiefly on the side towards Mexico, hence the earthquakes occur there; the Atlantic in the region of the Amazon is shallow, and the crust along the coast but little broken.

It appears therefore that the claim that earthquakes occur in the deltas of great rivers must be given up. Thus we get also a clearer view of the relief of the Indian Ocean, by which the Himalayas were formed; and the earthquakes occurring there now become more intelligible.

§ 24. *On Professor Suess' Theory that the Ægean Sea has Collapsed within Recent Geological Time, and on the Origin and Secular Movements of Asia Minor and Syria.*

Professor Suess holds that the basin of the Ægean Sea has sunk

down in recent geological time; and on the assumption that the globe is shrinking, he thinks the whole of Asia Minor may some day collapse, and thus connect the Pontus and the Caspian directly with the Mediterranean. According to the view here adopted nothing could be further from the truth than such an hypothesis. For, in the first place, we have shown that as the effect of cooling is insensible, the earth is not contracting; and, in the second place, that the movements of the crust are due to the action of a substratum just beneath, which in earthquakes behaves as fluid.

Moreover, the relative situation of the rocks about the *Ægean* Sea will be the same whether that sea has recently sunk down, or the whole of Asia Minor has been raised up. There is no historical evidence of the sinking of the *Ægean* Sea, except that furnished by the disturbances due to earthquakes, and the geological evidence is capable of a double interpretation. The prevalence of earthquakes in Asia Minor is a proof that subterranean movement is now going on there; otherwise such places as Apamea in Phrygia, Smyrna, Mitilene, Antioch and numerous other cities would not have suffered so much from earthquakes within historical times. The whole coast of Asia Minor and of Syria has been subject to severe earthquakes since the earliest ages; and the ruins of temples at such places as Palmyra and Balbec are to be explained partly by the effects of political revolutions and partly by the ravages of time, but more especially by the leveling influence of earthquakes.

In his work on "Earthquakes in the Light of the new Seismology," Major Dutton gives an account of the different kinds of seismic sea waves, and remarks that those in the eastern Mediterranean have usually been characterized by a preliminary withdrawal of the water before the wave returns to inundate the shore. Such waves are the only kind mentioned by Aristotle, which shows that they were familiar to the Greeks at an early age.

Now if the waves are predominantly of this class, just as along the west coast of South America, it follows that the sea bottom sinks, and has therefore been undermined in the process of elevating the mountains and the coasts. Asia Minor and Syria are covered with mountains of a complex character, and many movements of these mountains have been observed within the period

covered by history. No doubt the general movement is one of elevation, which corresponds to the sinking of the sea bottom implied in the seismic sea waves observed to come ashore after the terrible earthquakes by which the region is afflicted.

As the mountains are of recent formation, and extend entirely across Asia Minor, we may not hesitate in the belief that the whole of that region has been elevated within recent geological time. The sinking of the sea bottom prevailing in that part of the Mediterranean has often carried down the shores with it; but in a number of cases elevation has also taken place. Strabo, among the ancients, gives evidence bearing on this question; and Professor Suess, among the moderns, cites important changes which have taken place since the age of the Greeks. In "The Face of the Earth" (Vol. II., pp. 448-453), Suess mentions the subsidence of Smyrna and of the famous mausoleum in the Bay of Makri, as well as changes of level at Mitylene, Mermiridje and other places. It would be moderate to say that his explanations seem highly improbable, and it is really impossible that all of them can be correct. They rest on no general principle, but rather on improvised hypotheses.

The mausoleum at Makri can hardly have slid with the alluvial soil into the bay, as he maintains; for, judging by the photograph of the mausoleum which he gives, the alluvial base is not less than a mile wide, and thus would not slip, unless the substratum of rock were greatly inclined, which does not seem to be the case. The adjacent sea appears to be shallow, and all these circumstances are against the theory. Finally it is unlikely that the alluvium could be sufficiently settled by an earthquake to bring the mausoleum down to the level of the water, so that the tides would cover the lower part of it. It must have stood originally not less than 20 feet above the sea level, and 60 feet is a much more probable elevation. It is thus practically certain that the shore was carried down in the subsidence of the sea bottom, as happened when Helike sank beneath the waves in B. C. 373. In the case of the mausoleum the submergence may have been either sudden, or gradual. Darwin and Fitzroy observed the Chilean coast to subside slowly after it had been pushed up by the earthquake of 1835, and these slow move-

ments frequently occur, but are seldom recorded, because so much less obvious than sudden changes of level. In this way we may explain the changes of level at the Troad, Ephesus, the Peireus and other places mentioned by Strabo.

In the "Face of the Earth" (Vol. II., pp. 450-451), Professor Suess discusses the supposed changes in the level of the coast road on the Climax mountains in Pamphylia; and quotes Luschan, who says that "the sandy ground at the foot of these steep cliffs, which formerly offered a practicable road, is now (January, 1885) covered by the sea to a depth of four metres."

Here is Strabo's detailed description of this road as it was in the time of Alexander:

"About Phaselis, near the sea, are narrow passes through which Alexander conducted his army. There is a mountain called Climax. It overhangs the sea of Pamphylia, leaving a narrow road along the coast, which in calm weather is not covered with water, and travelers can pass along it, but when the sea is rough, it is in a great measure hidden by the waves. The pass over the mountains is circuitous and steep, but in fair weather persons travel on the road along the shore. Alexander came there when there was a storm, and, trusting generally to fortune, set out before the sea had receded, and the soldiers marched during the whole day up to the middle of the body in water." (Strabo's "Geography," Bohn's transl., Vol. III., p. 48.)

When one reads this clear and definite account, can there be any doubt of a subsidence since Strabo's time? In the campaigns of Alexander the soldiers did not march through more than one metre of water even during a storm; now the water is four metres deep, and if we could conceive the tallest of Alexander's soldiers raised to double height, by one standing on another's head, even the upper one could not keep his head above water. A subsidence therefore is undeniable, for a road would never have been thought of in four metres of water. It cannot be explained by a settlement of the road bed, which is mainly of stone, and gravel, covered with a thin layer of sand deposited by the waves; nor by the shaking down of the base during an earthquake, for such subsidences would be very small, and probably unequal at different points. It can have resulted only from the uniform sinking of the coast by at least three metres. This then is a well authenticated case of subsidence within the historical period.

It is impossible that all of the landslips assumed by Professor Suess to account for the numerous ruins beneath the sea, in Italy, Greece and Asia Minor, can be real; for as a rule such slips would depend on the breadth of the base, and the dip of the underlying strata. Unless the dip is very steep, sliding with a broad base is nearly impossible. Even with abundant underground water, the sliding of a broad mass is very difficult, for there will be rocks or obstructions somewhere which hold it fast. We have already remarked in regard to the mausoleum of Makri that the photograph given by Professor Suess (Vol. II., p. 449) shows that the alluvium is about a mile wide, and very flat. As the adjacent sea seems to be shallow, such a broad mass could not slide into it by the shakings of an earthquake. On the contrary it is clear that the coast sank and carried down the mausoleum with it, so that it is now washed by the tides and waves.

In conclusion we may hold that the Ægean sea probably is rising, and that within recent geological time Asia Minor and Syria have been raised from the sea; so that the Pontus and Caspian were formerly continuations of the Mediterranean, but are now cut off by the secular movement of the earth's crust. Many volcanoes have formerly been active in Asia Minor and Syria, which shows that geologically the region is one of elevation. Lava from beneath the Mediterranean, as well as the Pontus and Caspian, escapes under this region, and in the sinking of the sea bottom the shore is sometimes carried down with it, as in Pamphylia and other places which we have discussed. But in the course of geological ages movement of elevation predominates. Unless this were true, it is highly improbable that the whole region between the Mediterranean, Pontus and Caspian would be so powerfully afflicted by earthquakes.¹

¹ Since this paper was finished a severe earthquake has occurred at Bitlis in the mountains of Armenia. A press dispatch of April 4, from Constantinople, gives the following report from the Rev. Roy T. Lee, head of the American Mission at Bitlis:

"At ten o'clock in the forenoon of March twenty-ninth there burst upon us unannounced the worst earthquake experienced in forty years in these or the Ezerum volcanic regions. Such was its force that our city seemed to be in the jaws of some monster who would shake us into shreds as some mastiff does his game. Down came the plastering, the furniture was over-

There remains the possibility that the *Ægean* is being undermined by the expulsion of lava from beneath it, and it might be sinking so long as this process is at work; but it is difficult to doubt that the ultimate destiny of the *Ægean* is to be raised above the sea and become dry land, thus completing the bridge between Europe and Asia Minor. This general result is indicated by a study of the map. The numerous islands in the *Ægean* contradict the theory of permanent subsidence. The volcano which used to be active in the island of Lemnos, the eruptions in Eubæa mentioned by Strabo, the elevation of the Island of Delos, the repeated outbreaks near Thera, the numerous small islands which have been raised in the sea within the historical period,—all these phenomena point to elevatory movement affecting this whole region, because volcanic activity usually shows itself in regions of elevation. It is hardly possible that these several signs of elevation would have appeared if the *Aegean* were in process of secular subsidence. The activity of Mt. Ararat within historical time, especially in 1840, and of Mt. Demavend, south of the Caspian, and the outbreaks from other volcanoes in Asia Minor, all point in the same direction, and render it probable not only that the region is geologically one of elevation, but also that the Pontus and Caspian were thus cut off from the Mediterranean. The Dead Sea and the valley of the Jordan were cut off in like manner, and by this very earthquake process which has so often afflicted Syria within the period covered by human history.

The mountains in Syria parallel to the Mediterranean east coast, like those in Epirus and Dalmatia so beautifully parallel to the northeast shore of the Adriatic, were as clearly formed by the Mediterranean as the Andes, Rocky Mountains and Sierras were by the Pacific, which for millions of years has been uplifting a hemisphere unknown to the ancients.

As bearing on the subterranean processes at work under the *Ægean* Sea, by which Olympus and all the surrounding mountains turned, cracks were opened in strong walls, roofs were shattered and the rain poured in." In this case lava streams were evidently readjusting themselves under the earth's crust. The comparison of the shaking to that which a mastiff gives his game is most appropriate. It was just such shaking that proved so disastrous at San Francisco, Valparaiso, Kingston, and other places where lava was adjusting itself under the crust.

were formed, and repeatedly disturbed by earthshaking Poseidon, the following passages in Homer will not be without interest. The partition of the world among the principal deities is thus explained by Poseidon himself:

"For we are three brothers (descended) from Kronos, whom Rhea brought forth, Zeus and I and Pluto, governing the infernal regions, the third; all things were divided into three parts, and each was allotted his dignity; I in the first place when the lots were shaken was assigned to inhabit forever the hoary sea, and Pluto next obtained the pitchy darkness; and finally Zeus received the wide heavens in the air and the clouds; but the earth is still the common property of all, and lofty Olympus." (*Iliad*, XV., 187-194.)

The account describing Poseidon's mansions beneath the Ægean sea is as follows:

"Nor did king Poseidon keep a vain watch; for he sat aloft upon the highest summit of the woody Thracian Samos, admiring the war and the battle. For from thence all Ida was visible, and the city of Priam was visible, and the ships of the Greeks. Then coming out of the sea, he sat down, and he pitied the Greeks, subdued by the Trojans, and was very indignant with Jove. But presently he descended down from the rugged mountains, rapidly advancing on foot, and the high hills and woods trembled beneath the immortal feet of Poseidon, advancing. Thrice indeed he strode, advancing, and with the fourth step he reached Ægæ, his destined goal. There distinguished mansions, golden, glittering, ever incorruptible, were erected to him in the depths of the sea. Coming thither, he yoked beneath his chariot the brazen footed steeds, swiftly flying, crested with golden manes. But he himself placed gold about his person, took his golden lash, well wrought, and ascended his chariot. He proceeded to drive over the billows and the monsters of the deep sported beneath him on all sides from their recesses, nor were ignorant of their king. For joy the sea separated; and they flew very rapidly, nor was the brazen axle moist beneath. And his well-bounding steeds bore him to the ships of the Greeks.

"Now there is an ample cave in the recesses of the deep sea, between Tenedos and rugged Imbrus. There earthshaking Poseidon stopped his horses, loosing them from the chariot and cast beside (them) ambrosial fodder to eat." (*Iliad*, XIII., 10-35; Buckley's Translation.)

The Ægean Sea was the part of the Mediterranean with which Homer was best acquainted, yet he possessed fairly accurate knowledge of many seas and many lands; and the fact that out of all this domain of ocean he placed Poseidon's chief abode beneath the Ægean indicates that if he did not possess divine wisdom, with regard to earthquake forces, he at least chose for the earthshaker's dominions the very spot which would be selected to-day, in the light of the history of thirty centuries since the composition of the *Iliad*.

VI. CONCLUSIONS.

It now remains to sum up very briefly the chief conclusions at which we have arrived. Different arguments appeal with unequal force to different minds, and doubtless there are some who will hesitate at departing from the views recently current in the sciences which deal with the earth. Others who have more or less despaired of definite results under the uncertainty and confusion heretofore existing, will naturally be slow to believe that the laws and order of nature are so simple. But these varieties of temperament will not change the force of the several arguments for a single cause shown to underly the most varied phenomena.

We have endeavored to show not only that the cause assigned in the paper on earthquakes is adequate to account for the observed phenomena, but also, through the process of exclusion, that no other possible cause is at work in world-shaking earthquakes. In this survey of the whole field we were led to reject the theory of contraction and secular cooling as an effective agency in modifying the surface of the earth. And we contrasted the absence of world-shaking earthquakes in an inland region like Colorado and Kansas or the Desert of Sahara with their constant occurrence along the Andes, as a proof that the forces involved depend on the ocean and not at all on secular cooling. For if this latter is a real cause it should be at work inland as well as along the sea coasts. These considerations therefore seem to establish the cause which has formed mountains, and wrinkled the earth's crust in a very complicated manner.

In the study of this question consideration was carefully restricted to earthquakes of the world-shaking class, because the great disturbances were held to be best adapted to disclosing the true nature of the processes hidden beneath the earth's surface. The problem was thus simplified and cleared of the confusion that would necessarily have resulted from the simultaneous consideration of all earthquakes, both large and small.¹ The slight shocks may be due to various

¹ Viewing the earth as an elastic solid under stresses of varying intensity several eminent mathematical physicists have recently considered the dilatational stability, or the stability of the crust under its own gravitation, when some of the surface matter is removed. After calculating these hypothetical effects by elegant mathematical methods, some of them have inferred that when denudation takes place under geological agencies, thus

causes, but are mainly traceable to the effects of great earthquakes of the present and past, which have left the earth's crust much broken and distorted and often in an unstable condition.

This is clearly shown by the after-shocks which follow world-shaking earthquakes in great numbers and for a long time. Thus nearly all earthquakes result directly or indirectly from the great earthquakes; but the movement in different cases is doubtless very different, and consists largely in the gradual adjustment of the disturbed crust. Hence our principal conclusions are the following:

1. The cause of world-shaking earthquakes, mountain formation, and kindred phenomena connected with the physics of the earth, is the secular leakage of the ocean bottoms, which gives rise to the development of steam beneath the earth's crust.

2. This vapor and no other is the cause of these disturbances, because if any other vapor were at work beneath the crust some of it would escape through the vents of volcanoes, and become recognizable by observation.

lowering the level, the crust, having the weight at length removed, would spring upward, perhaps recovering much or all of the elevation lost by denudation. The following considerations will show that this reasoning as applied to geology is likely to be fallacious. Under ordinary conditions denudation is very slow, and the unloading too gradual to produce anything but the most insensible relief upward. We can see that this will be true by considering how little a corresponding increase of load would sag the level. If for example the load be a mass of soil or of rock 100 feet deep, the sagging where the ground is hard, but not solid rock, would be of the order of a few inches. The removal of such a load would no doubt give rise to a similar restitution upward, but no more; and as such denudation in nature is excessively slow, the springing upward is infinitesimal, and requires nearly infinite time. Therefore no important geological effects depend on such causes, though perhaps insensible surface movements may thus arise. But they would scarcely claim the title of microseisms and certainly could not rise to the dignity of earthquakes; for even if landslides should occasionally develop in this way the resulting shocks would be mere local tremors. No heavy earthquakes could depend on such causes, for if so they should be observed far inland as well as along the sea coast, which is contrary to observation. Accordingly while such reasoning is learned, and mathematically interesting, it has only a slight physical basis, and as applied to geology is deceptive and misleading. Until the true cause of world shaking earthquakes is placed beyond doubt and fully recognized, the consideration of such infinitesimal influences as this had better be passed over, because it simply bewilders the subject. In this connection particular attention is called to the footnote on pp. 408-409 of the paper on the cause of earthquakes.

3. The distribution of volcanoes, mountains, and earthquakes shows that all these phenomena depend upon the sea and water generally; wherefore the depth of earthquakes is shallow and so far as is known never exceeds forty miles.

4. The principal purpose of earthquakes is the elevation of land, which has made possible the development of the higher forms of life upon the earth.

5. Plato, Aristotle, Strabo and Pliny all held that water and air penetrate into the earth, through hollows, fissures and crevices, thus developing vapor in the heated interior, a part of which is expelled from volcanoes. And they also held that earthquakes are due to the tension of elastic vapors seeking to escape and diffuse themselves in the atmosphere, whether these vapors break through and form eruptions, or remains hidden in the earth.

6. The movement of streams of lava beneath the earth's crust, which occurs in every world-shaking earthquake, is the modern view of Plato's *Pyriphlegethon*. Though Aristotle and his successors associated earthquakes with the sea, they do not appear to have held any definite theory of the movement of the fluid beneath the earth's crust. From Strabo's remarks, however, it appears probable that they considered mountains to be formed by earthquakes and eruptions.

7. Aristotle correctly associated seismic sea waves with earthquakes; and even Homer assigned these great disturbances of the sea to Poseidon's trident, which was also the means employed for raising up islands from the bottom.

8. The withdrawal of the water from the shore after an earthquake and its return as a great wave, was familiar to Aristotle, and is implied in his description of the sinking of *Helike* in 373 B.C.

9. This pathetic calamity was due to the subsidence of a portion of the sea bottom in the gulf of Corinth, after lava had been expelled from beneath it, and pushed under the mountains of Arcadia.

10. The elevation and subsidence of the land long ago contended for by Strabo is now proved to occur, and examples of this movement may be cited in ancient as well as in modern times. While Strabo clearly states the fact of such movement he seems to have been doubtful of the cause. Aristotle does not give the cause of these changes,

though he no doubt associated them with earthquakes and the sea, which seems to be the view also of Plato, so far as one can judge from his description of the sinking of Atlantis.

11. The theory here developed was therefore roughly outlined and more or less anticipated by the leading Greek philosophers, especially by Aristotle; and as formulated by them it continued to be held till modern times, though of late years it has been quite abandoned, owing to the unfortunate development of the theory of tectonic earthquakes.

12. In the present paper we have examined carefully the question of the temperature of the earth, and have given what appears to be the most probable law of its internal distribution.¹ No external effects traceable to deep-seated movements of heat are discoverable, and we have therefore concluded that the nucleus of the globe is now and always has been quiescent.

13. The deformations of the earth's surface are found to be due to earthquake processes working just beneath the crust, and to original inequalities of the surface dating from the genesis of the moon, which gave rise to the principal ocean basins.

14. The two methods for estimating the period since the consolidation of the globe agree in indicating that it was of the order of ten million years, and thus by no means so long as many geologists have been inclined to believe. Moreover, appreciable cooling has not extended below the depth of some forty miles, or one one-hundredth of the radius, so that it is confined almost wholly to the crust.

15. It is estimated that the Andes might be formed in something like three million years, and the plateaus west of the Rocky Mountains in not more than five million years.

16. When the tension of the imprisoned steam under the oceans becomes very great, it finally causes the crust to yield along the margins, and mountains are pushed up where the crust breaks parallel to the coast. When an avenue of escape is thus once opened for the lava, it continues active, and the mountains grow higher and higher, unless meanwhile the sea recedes to too great a distance.

¹ A comparison of the small figure in the right hand upper corner of the diagram with the larger figure F shows how one of the distributions of temperature passes into the other by continuous flow of the heat outward while the planet is consolidating. The monotonic curve thus becomes an ellipse.

17. At one time or another the principal oceans form mountains all around them, but in any one geological age the relief may be chiefly on one side, except when the ocean is of very great extent, like the Pacific,¹ which therefore is active all around, and obtains some internal relief by the formation of numerous islands.

18. We have shown that just as soon as the exploding lava acquires sufficient tension or elastic pressure to lift the crust along a fault line, a displacement occurs there, and the lava spreads beneath the block thus moved, giving relief along the path of least resistance. It is the enforced movement of these subterranean lava streams which shakes down cities and devastates whole countries.

19. It is found that secular cooling is so very slow and so small in amount that it has no sensible effect on the physics of the globe. Accordingly it is shown that the earth is not now shrinking, nor has it been at any time since the consolidation began.

20. On the contrary the formation of pumice everywhere beneath the land, as it is elevated by the steam forming under the oceans, is raising the level of the continents, in spite of erosion. And as the oceans are being gradually narrowed by the recession of the sea, after successive mountain chains are formed—some of the water sinking beneath the earth's crust, and the rest collecting into a smaller area, here and there growing deeper when lava is expelled from beneath the margins—it may well be that the ocean level is nearly stationary, or rising slightly with respect to the centre of the earth, though there is a secular lowering of the strand line relatively to the land. Accordingly so far from contracting the earth may be in reality very slightly expanding. This secular expansion is due to the formation of pumice nearly everywhere beneath the crust.

¹In his *Manual of Geology*, 1863, the late Professor J. D. Dana came surprisingly near many of the views reached in the present investigation. He pointed out with great clearness that the continents not only are built on one model, with the mountains around their borders, while the interior is a depressed basin, but also that the highest border is on the side of the greatest ocean, and conversely. In speaking of this fundamental law he remarks that "the relation between the extent of the oceans and the height and volcanic action, etc., of their borders proves that the amount of force in action had some relation to the size and depth of the ocean basin. The Pacific exhibits its greatness in the lofty mountains and volcanoes which begirt it."

21. The calculated fall of temperature for the whole earth of 10° C. (Tait) and of 45° C. (Daniell) in 100 million years, with the cubical coefficient of expansion of 0.00002, found by experiment for average rock of the earth's crust, would produce a shrinkage of only 0.26 and 1.16 miles respectively. But if the period since the earth's consolidation be only about one tenth that here assumed, according to the usage of geologists, the corresponding contraction would certainly not much exceed one tenth of these values, or say 137 and 612 feet. These values are so very small that the uplifts due to earthquakes might easily cause the globe to expand rather than contract. Accordingly if our present data do not enable us to conclude that the earth is undergoing secular expansion, we may at least conclude that it certainly is not sensibly contracting. Its dimensions seem to have been nearly stationary since the consolidation began.

22. The principal phenomenon heretofore requiring the theory of contraction is the formation of mountains; but Rev. O. Fisher has shown that this cause is quite inadequate, and in the paper on the cause of earthquakes we have developed the theory of mountain formation depending on the sea. The doctrine of the secular contraction of the globe must therefore be entirely abandoned, and the explanation of the phenomena sought in other causes.

23. By the existence of unstable pinnacles of rock formed by the gradual processes of geological time it seems to be proved that no deep and very powerful convulsions of our globe, except the ordinary shocks noticed in earthquakes, have taken place in many millions of years. We must therefore ascribe to ordinary world-shaking earthquakes the highest geological significance. These forces depending on the sea produce both elevations and depressions of the land, and explain all the phenomena of movement witnessed upon the earth.

24. In the development of these views Aristotle and Strabo occupy the foremost places among the ancients; Humboldt, Lyell and Darwin among the moderns; while Fourier and Lord Kelvin naturally claim the leading places among the illustrious physicists who have occupied themselves with these great problems of the heat of our planet.

BLUE RIDGE ON LOUISE,

MONTGOMERY CITY, MISSOURI, March 22, 1907.

In conclusion it remains¹ to notice one difficulty which has occurred to some readers, and thus should perhaps be given further elucidation. By those who have not made a careful study of the porosity of matter under great fluid pressure, it seems to be felt that notwithstanding the apparently conclusive character of Daubrée's experiments, they form a rather slender experimental basis upon which to build a satisfactory explanation of the sinking of sea water through the earth's crust, which is composed of from ten to twenty miles of solid rock like granite. That this supposed difficulty is devoid of real foundation will appear from the following considerations, which enable us to show that the oceans do experience such a secular leakage, and to prove this fact quite independently of Daubrée's experiments.

1. In the paper on the cause of earthquakes, § 15, it is shown that the chances are at least (100 billion)⁶ or a decillion decillions to one, that the mountains are formed parallel to the shore by a true physical cause depending on the oceans. This is of course an absolute certainty. The mountains therefore depend in some way upon the sea. To perceive most clearly what this dependence is, we may notice, as in the former paper, that the elevation of the Andes has been accompanied by the sinking of the adjacent sea bottom into a parallel trough of about the same volume. That lava has been expelled from beneath the sea and pushed up under the land is indicated by the depression in the sea bottom parallel to the Andean Cordillera; and this inference drawn from the geometrical evidence of the surface of the lithosphere is confirmed by direct observations, made within the historical period, on those earthquakes which produce sensible uplifts of the coast and simultaneous subsidences of the sea bottom, as shown by the accompanying seismic sea waves. Moreover unbroken continuity between the small uplifts and subsidences observed within the historical period and the vastly greater movements gradually accumulated during past geological ages is established by the deposits of shells and fossil beds found at great heights in the Andes, and by the deep depressions in the adjacent oceanic trough. It is therefore undeniable that in the course of long ages

¹ This closing discussion, with the exception of the last sentence, was added April 18, 1907.

the mountains and coast have been greatly elevated and the adjacent sea bottom correspondingly sunk down.

2. The earthquake shocks producing these effects are found to occur at a depth of some 15 miles, where the pressure is so great that no cavities in the earth can possibly exist. Therefore there are neither voids at this depth beneath the mountains nor corresponding increases of density beneath the sea where the bottom has subsided, but vast quantities of matter have been expelled from beneath the ocean and pushed up under the adjacent mountains. These phenomena, as observed in South America, are clear and indisputable, and admit of but one interpretation: namely, that the Andes have been formed by successive earthquakes which have expelled the lava from beneath the bed of the adjacent sea, and thus upraised the crust into some of the mightiest mountains of the globe.

3. The next question then becomes: How is the lava expelled from under the sea? We say lava rather than solid rock, because owing to the increase of underground temperature, at a depth of 15 to 20 miles below the surface, where the world-shaking earthquakes originate, the matter must be essentially molten, in spite of the great pressure to which it is subjected. We therefore answer that since the earth is neither contracting nor experiencing any other sensible changes from secular cooling, the expulsion can be accomplished only by explosive vapors such as are emitted from the neighboring volcanoes, which often break out into eruption simultaneously with an earthquake noticed to produce an elevation of the shore and a sinking of the sea bottom. This vapor therefore can be nothing else than common steam.

4. Now the steam developing beneath the earth's crust and producing earthquakes and volcanic activity can be traced to but two possible sources: First, the original magma of the globe, which, in default of a better explanation, has been frequently invoked by the geologist; Second, the secular leakage of the ocean bottoms effected through 15 miles of solid rock like granite, which naturally appeals to the physicist. If the escaping steam, or any sensible part of it, came from the central magma of the globe, volcanoes and earthquakes necessarily would occur in the interior of continents as well as along the coasts, on islands, and in the depths of the sea. For

the continents are large areas, and altogether cover more than one fourth of the total surface of the globe; yet the volcanoes and world-shaking earthquakes are confined to the neighborhood of the oceans or other large bodies of water.

5. It clearly follows therefore that the agitating vapor does not come from the central magma of the globe, but must come from the secular leakage of the ocean bottoms. This is unmistakably indicated by the most overwhelming evidence of nature.¹

¹ Newton's rules of reasoning in natural philosophy should be borne in mind here:

RULE I. *"We are to admit no more causes of natural things, than such as are both true and sufficient to explain their appearances."*

"To this purpose the philosophers say, that Nature does nothing in vain, and more is in vain, when less will serve; for Nature is pleased with simplicity and affects not the pomp of superfluous causes."

RULE II. *"Therefore to the same natural effects we must, so far as possible, assign the same causes."*

"As to respiration in a man, and in a breast; the descent of stones in Europe and in America; the light of our culinary fire and of the sun; the reflection of light in the earth, and in the planets."

RULE III. *"The qualities of bodies, which admit neither intension nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever."*

Newton's explanation of this rule is too long to be quoted here; but it is worthy of the most careful study.

RULE IV. *"In experimental philosophy we are to look upon propositions collected by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions."*

"This rule we must follow that the argument of induction may not be evaded by hypotheses."

In the investigation of the physics of the earth involving many hypotheses of very unequal weight this last rule acquires special importance. If therefore some trifling details are not yet explained or understood we must not on that account reject the cause gathered by a general induction of all the related phenomena of the globe. On the contrary we must adhere to the cause "as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions," in order that the "argument of induction may not be evaded by hypotheses." In his explanations of Rule III. Newton remarks: "We certainly are not to relinquish the evidence of experiments for the sake of dreams and vain fictions of our own devising; nor are we to recede from the analogy of Nature which uses to be simple, and always consonant to itself."

6. Therefore it incontestably follows that the explosive vapor operating in earthquakes, volcanoes, mountain formation and kindred phenomena connected with the physics of the globe, comes from the secular leakage of the ocean bottoms, effected through the earth's crust, composed of some fifteen miles of solid rock like granite.

7. Accordingly it necessarily follows also that Daubrée's experiments are applicable to layers of rock twenty miles thick, when the water is subjected to the great fluid pressure constantly operating in the deepest oceans. Our fundamental proposition is thus proved quite independently of Daubrée's experiments. In fact by simply observing the phenomena of nature one might infer that such experiments as those made by Daubrée would be possible under good laboratory conditions.

8. In the case of our thinly encrusted planet so largely covered with water the natural arrangement between the overlying oceans and the underlying molten globe constitutes a laboratory of the most imposing magnitude, infinitely transcending anything ever conceived by man, with gigantic experiments constantly going on. All that is needed therefore is for the philosopher to interpret nature's stupendous operations, which unfortunately only too often prove disastrous to human life, because of our ignorance and disregard of natural laws. The highest duty of the philosopher is to discover these laws and make them available to the world, so as to contribute as much as possible to the repose and safety of mankind.

9. According to the theory here developed earthquakes and related phenomena, which have so afflicted the world from the earliest ages, are not much to be dreaded when their laws are understood, and adequate precautions are taken to secure the building of safe houses. When, however, people live near active volcanoes protection is not always possible, though fortunately it is generally within reach at most places visited by earthquakes throughout the world.

10. But as great multitudes of people live in cities by the sea they are also subjected to the dangers arising from seismic sea waves; yet if a place of refuge exists they usually have ample time to escape. And even the ships in the harbor will generally be safe if they promptly put to sea on the first sign of the withdrawal of the

water after the earthquake, which always indicates that the sea bottom has sunk. Thus by the study of the laws of the physical world, and the diffusion of the resulting useful knowledge, a great measure of safety may be secured from some of the most dreadful forces in nature, and in the course of time the interests of civilization enormously conserved.

When we reflect over these results and contemplate the harmony thus established in many branches of the physical sciences, is it not obvious that Newton's belief that the great laws of nature are simple may with great advantage still be borne in mind by those who wish to arrive at the ultimate causes which lie at the basis of natural philosophy?

BLUE RIDGE ON LOUISE,

MONTGOMERY CITY, MISSOURI, April 18, 1907.

ADDENDUM.

Further Considerations on the Earthquake at Helike and Bura,
373 B. C.

Some time after the foregoing was finished it occurred to me to consult Grote's "History of Greece," in the hope of obtaining further light on the famous disaster at Helike; and from his references (Vol. X., p. 157) to Diodorus Siculus, Ælianus and Pausanias I have prepared the following addendum:

1. *Diodorus Siculus, Book XV., Chap. V.*—It is well established that this historian flourished in the reign of Augustus, but the date of his death is not known. The translation here followed is that of G. Booth, London, 1700. This is an old work, and the style of writing is antiquated, but the meaning appears to be clear.

"Afterwards when Asteius was chief magistrate at Athens, and six Military Tribunes, viz. Marcus Furius, Lucius Furius, Aulus Posthumus, Lucius Lucretius, Marcus Fabius and Lucius Posthumus executed the office of Consuls at Rome, there happened such dreadful earthquakes and inundations in Peloponnesus (throughout all the cities and over all the country) that are incredible to relate. For never in any former Ages did the like calamity fall upon the Grecian Cities, which were now swallow'd up together with their inhabitants; and certainly some Divine Power contrived and executed this remarkable ruine and destruction of Mankind: Nay the time when it was done aggravated the gréatness of the calamity. For the earthquake hapned not in the day (when the distressed might have found out some way or other to have helped themselves) but in the night; and

when the houses by violence of the shake fell down in confused heaps; so that (by the darkness of the night and the suddenness of the ruine) men were in that perplexity that they knew not which way to turn themselves for security; in so much as the greatest part of the inhabitants (buried in the rubbish of the houses) miserably perished. But as soon as it was day some came running out of the houses, and thinking they had escaped the danger, fell into a far greater and unexpected mischief; for the sea raged to that degree, and broke in with that violence that it swallowed up them and their houses together. Two cities of Achaia, one called Helica and the other Bura, chiefly suffered by this sad accident, of which two Helica was of the greatest account of any of the cities of Achaia.

"There was a very hot dispute concerning the cause of this evil. Indeed the natural philosophers do generally ascribe all such events to Natural Causes, and necessary circumstances, and not to any Divine Hand; But they who have more reverend thoughts and sentiments of a Deity, give a very probable account of this matter, that this destruction was the effect of the Anger of the Gods, for the impious violation of the rights of Religion, of which we shall give a more particular account. . . ."

After describing the impious conduct of the Heliconians, Diodorus continues:

"Upon this they of Helica siezed upon all the goods of the Ionians and committed the Ambassadors to Prison, and so carried it very impiously towards the Deity. Therefore they say Neptune being angry, to revenge himself upon their impiety (by this earthquake and inundation of the sea) brought this grievous calamity upon those cities. And that it was done by him they use this for an argument: *That it is generally believed that this God hath the power of inundations and earthquakes in his own hands*; and that *Peloponnesus* had been ever reputed the Habitation of *Neptune*, and the country dedicated to him and that all the Peloponnesian cities worshipped this God above all others. Besides this, they give a further reason of said accident. There are (as they say) in *Peloponnesus* great cavities underground, which by the sea flowing here and there through the earth are turned into great Ponds and Lakes of water. And indeed it is very certain that there are two rivers in that Peninsula, which apparently fall into the caverns of the earth. For the Rivers which ran by *Pheneum* in former Ages sank in one place into the earth, and became invisible, being swallowed in these caverns underground. Another was lost at a great opening of the earth at *Stymphius*, and ran unseen underground for the space of two hundred stages, and rose again near the city *Argos*." (Diodorus Siculus, Lib. XV., Cap. V., translated by G. Booth, London, 1700.)

2. *Ælianus, De Natura Animalium*.—This well known author probably flourished in the time of the Emperor Hadrian. His account of the earthquake at Helike is short but very clear. As given in Teubner's edition of the works of *Ælianus*, Leipzig, 1864, the account (xl., 19) runs thus:¹

¹ Rev. Theodore F. Burnham very kindly verified the translation now offered.

"When a house obviously is about to be overthrown, the mice which are in it leave along with the weasels, and they anticipate the disaster and emigrate. This indeed they say took place also in Helike. For when the Heliconians were engaged in religious worship, upon the arrival of the Ionians, they sacrificed them (the animals) upon the altar, whence forthwith (this is Homeric) certain gods manifested signs unto them; for five days before the disappearance of Helike all the mice that were in it, and weasels and serpents, millipedes and beetles and the rest of things of this kind, crept forth together into the road leading to Cerynea. And the Heliconians seeing what had happened marveled indeed, but were unable to understand the cause. And when the aforementioned animals had left the place, an earthquake occurred in the night, and the city collapsed, and, overflown by a great wave, Helike disappeared; and by chance ten vessels of the Lacedemonians lying at anchor perished in the rush of the waters. And it came to pass necessarily in respect to the vengeance upon the rowers of the impious men, that justice demanded their lives. And in proof of this judgment, Pantocles, the Lacedemonian, having set forth to go through Sparta to reach those absent from the force with Dionysus who were in Cythera, when he had seated himself on the bench of the Ephors, was torn to pieces by dogs."

3. *Pausanias, Description of Greece, Book VII., Caps. XXIV.-XXV.*—It is well known that this famous traveler lived in the time of the Antonines, and probably finished his work in the reign of the Emperor Marcus Aurelius, about 170 A. D. A very excellent translation with critical introduction and copious commentary, the whole in six volumes, has recently been published by J. G. Frazer, M.A., LL.D. (Glasgow), fellow of Trinity College, Cambridge (Mac-Millan & Co., London, 1898). The following accounts of the destruction of Helike and Bura are taken from Frazer's translation.

In the description of Achaia, Book VII., Chap XXIV. (pp. 365-366) Pausanias says:

"Going on you come to the river Selinus, and forty furlongs from Ægium is a place Helice on the coast. Here there used to be a city Helice, and here the Ionians had a most holy sanctuary of Heliconian Poseidon. Their reverence for that god has survived to the present day, in spite of their expulsion by the Achæans and their migration first to Athens, and afterwards to the coast of Asia. At Miletus, on the way to the spring of Biblis, there too is an altar of Heliconian Zeus in front of the city; and in Teos, too, the Heliconian god has an enclosure and an altar which are worth seeing. Homer also refers to Helice and Heliconian Poseidon. 5. But in after time the Achæans of Helice forced some suppliants from the sanctuary, and put them to death. The wrath of Poseidon did not tarry. The land was instantly visited by an earthquake, which swallowed up not only the buildings, but the very ground on which the city had stood. Ominous signs, vouchsafed by the god, foretell the approach of great and far-reach-

ing earthquakes. The nature of the sign is generally the same. For earthquakes are preceded either by heavy and continuous rains or long droughts. The weather, too, is unseasonable. If it is winter, the weather is sultry; if it is summer, there is haze, and the sun's disc appears of an unusual colour, slightly inclining either to red or dun. Springs of water mostly dry up. Sudden gusts sometimes sweep across the country, blowing the trees down. At times, too, the sky is shot with sheets of flame. Stars are seen of an aspect never before known, and strike consternation into beholders. Moreover, a mighty murmur is heard of winds blowing underground. And many more signs there are whereby the god gives warning of the approach of violent earthquakes. The character of the shock itself is not always the same. The original observers and persons instructed by them have been able to distinguish the following classes of earthquakes. The mildest form of earthquake—if so dire a calamity can be thought to admit of alleviation—is when the first shock which levels the buildings with the ground, is counteracted by an opposite shock which raises up what the first had knocked down. In this kind of earthquake you may see columns, which had been all but hurled from their bases, rising to the perpendicular, and walls which had been cracked closing up again; and beams, which the shock had caused to slide out, return to their places, and similarly rifts made in conduits and water-channels are cemented better than they could have been by a craftsman. The second kind of earthquake destroys everything that is the least unsteady; whatever it strikes it instantly overthrows, as with the blow of a battering ram. The deadliest kind of an earthquake is illustrated by the following comparison. In an unintermitting fever a man's breathing is quick and laboured, as is shown by symptoms at various points of the body, but especially at the wrists; and they say that in the same way the earthquake dives under buildings and upheaves their foundations, just as molehills are pushed up from the bowels of the earth. It is this kind of shock alone that leaves not a trace of human habitation behind. They say that the earthquake at Helice was of this last kind, the kind that levels with the ground; and that, besides the earthquake, another disaster befell the doomed city in the winter-time. The sea advanced far over the land and submerged the whole of Helice, and in the grove of Poseidon the water was so deep that only the tops of trees were visible. So that between the suddenness of the earthquake and the simultaneous rush of the sea, the billows sucked down Helice and every soul in the place. 7. A like fate befell a city on Mount Sipylus; it disappeared into a chasm, and from the fissure in the mountain water gushed forth, and the chasm became a lake named Saloe. The ruins of the city could still be seen in the lake until the water of the torrent covered them up. The ruins of Helice are also visible, but not so clearly as before, for they have been eaten away by the brine."

Again in Chapter XXV. (p. 367) these additional remarks are added:

"The Lacedæmonians also slew men who had taken refuge in the sanctuary of Poseidon at Tænarum; and not long afterward their city was shaken by so prolonged and severe an earthquake, that not a house in Lacedæmon stood the shock.

"2. The destruction of Helice took place when Astius was archon at Athens, in the fourth year of the hundred and first Olympiad, in which Darnon of Thurii was victorious for the first time. As none of the inhabitants survived, the territory now belongs to Ægium. . . .

"5. Returning from Cerynea to the high road, and proceeding a little way along it, we turn off a second time from the sea to the right in order to reach Bura. The town stands on a mountain. They gave it the name of a woman, Bura, whose father was Ion, son of Xuthus, and whose mother was Helice. When the god blotted out Helice from among men, Bura also was overtaken by a severe earthquake which spared not even the ancient images in the sanctuaries. Such people as chanced at the time to be away at the wars or on other business were the only survivors, and they rebuilt Bura. There is here a temple of Demeter, another of Aphrodite and Dionysus, and another of Illithia. The images are of Pentelic marble, and are works of Eluclides, an Athenian. The image of Demeter is clothed. There is also a sanctuary of Isis.

"Having descended from Bura in the direction of the sea, we come to a river named Buraicus and to a small image of Hercules in a grotto. This image is also surnamed Buraicus, and there is a mode of divination by means of dice and a tablet. The person who inquires of the god prays before the image, and after praying he takes four dice and throws them on the table. Each die has a certain figure marked on it, and the meaning of each figure is explained on the tablet.

"The straight road from Helice to the Hercules is about thirty furlongs. Going on from the Hercules you come to the mouth of a river which comes down from a mountain in Arcadia, and never dries up. The river is called the Crathis, and Crathis, too, is the name of the mountain which are its springs. From this Crathis the river beside Crotona in Italy got its name. On the bank of the Achæan Crathis once stood the city of Ægæ; they say that in course of time it was deserted by its inhabitants, because they were a feeble folk."

In his excellent and lucid commentary on Pausanias' "Description of Greece," Frazer says of *Bura*:

"Between the Boupousia (Cerynites) and Kalavryta (Buraicus) rivers there rises a massive hill, which falls away on the south and west in a line of stupendous precipices. This is the hill or mountain of Bura; it is now called by the natives *Idra*. On the north the hill is separated from the sea by a strip of level coast land; on the southern side it is connected by a neck or saddle (which is, however, far below the summit of the hill) with the loftier mountains which begin here and stretch away into Arcadia. On this neck or saddle are the remains of Bura. They consist of extensive, though insignificant, remains of walls and foundations, spread along the southern part of the western foot of the hill as far as the copious spring which gushes from the bottom of the precipice. Among the ruins is a chapel of St. Constantine, which presumably occupies the site of an ancient sanctuary. Mixed with the ruins are huge blocks of rock which appear to have been hurled from the beetling crag above by an earthquake, perhaps the same earthquake which destroyed the city.

"The whole neighborhood gives one the impression that it has been subjected to gigantic convulsions of nature. The crags tower up to dizzy heights above the traveler, and the rivers find their way through tremendous gorges to the sea.

"At the southwestern foot of the hill of Bura, where the precipices rise highest, lie the ruins of the ancient theatre, with remains of fifteen rows of seats; the orchestra is about 32 paces broad. From some of the seats there is a fine view of the Corinthian Gulf, with the mountains of northern Greece rising behind it. A few remains of the town wall may be seen below the theatre.

"The citadel of Bura probably occupied the summit of the hill. The western face of the hill is a sheer wall of rock; a single path here leads to the summit."

From this account it is clear that most of the site of Bura is too high above the sea to have been inundated by the seismic sea wave of 373 B. C., and that the damage was due principally to the violent shocks during that dreadful earthquake. Pausanias says that it was so violent "that it spared not even the ancient images in the sanctuaries. Such of the people as chanced to be away at the wars or on other business were the only survivors, and they rebuilt Bura." This accords well with descriptions of the yawning chasms at Bura given by Aristotle, Lucretius and other writers.

It also appears that according to the authorities available to Pausanias, Helike subsided so much that only the tops of the trees in the grove about the temple of Poseidon remained above the water. As this temple could not well have been less than fifty feet above sea level, the total subsidence must have been about a hundred feet. This effectively disposes once for all of the claims of Professor Suess and others that it was caused by the breaking loose of alluvium from the older geological formations. It is therefore placed beyond doubt that under the throes of the earthquake the bed of the Gulf of Corinth gave down and thus brought on the most famous inundation of antiquity.

There seems to have been many earthquakes that year (373 B. C.), but unfortunately our accounts are too uncertain to enable us to fix upon the exact order of events. But as Pausanias says that "besides the earthquake another disaster befell the doomed city in the winter-time," we may safely infer that in all probability the sinking of the sea bottom took place with one of the later shocks, as sometimes happens in South America. This agrees also with the

somewhat vague language of Diodorus Siculus, who says that the sea wave occurred in the day following the earthquake at night. None of these accounts are to be too implicitly trusted, because Pausanias says no one at Helike escaped, while Diodorus implies that some persons were escaping when the wave overwhelmed the city.

If there had been a series of slight but incessant earthquake shocks previous to the terrible earthquake at night, the account given by Ælianus of the exodus of mice, weasels, and other animals from the town becomes very intelligible; but here again we must beware of reposing too much confidence in narratives composed after the lapse of several centuries. Of all the contemporaries of this event, Aristotle was best qualified to speak with authority; but, as we have seen, his account gives only the leading facts without the details added by later writers, and is impossible to estimate how many of these details are authentic.

On the whole it appears to be certain that there were many premonitory signs of the disaster, in the form of a series of preliminary shocks extending through several months and felt all over the Peloponnesus; and it seems equally certain that the greatest shock occurred in the night. This leveled Helike and Bura to the ground, and was due to the expulsion from beneath the bed of the sea of a mass of lava which was pushed under the mountains in Arcadia, causing great chasms to open near Bura. In consequence of this undermining of the sea bottom it afterwards gave down nearly a hundred feet, but we cannot be sure whether the subsidence took place with the great shock in the night, or followed from one of the violent aftershocks the next day. On the whole the latter view seems the most probable, since there is no reason why the sea bottom once undermined might not sink with one of the violent after shocks which always follow great earthquakes.

When we consider the interval of time by which we are removed from this great disaster, it is quite remarkable that our knowledge of it should be so complete as it is. Plato was then in his fifty-fourth year, at the height of his powers, and at the head of the Academy in Athens, and Aristotle was a boy eleven years old; but the impression made upon contemporary Greek thought was proportionate

to what might have been expected from the sudden obliteration of Helike, at once the most important city in Achaia, and the center of the Panionian league, owing to the prosperity and increasing prestige it had enjoyed since the days of Homer. As Aristotle tries to account for the disaster by the theory of opposing winds, it is evident that it must have been a subject of keen speculation among the leading Greek philosophers. Although the explanation given by Aristotle is now invalidated by the advancement of science, he was entirely correct in ascribing this dreadful calamity to the agitation of vapors confined within the earth, which in seeking release finally brought on the cataclysm.

There are few results in science of deeper interest than those obtained by a principle which enables us to remount to the earliest ages of history, and to explain phenomena contemporaneously observed by the greatest minds of antiquity. This impressively illustrates the difference between a discovery disclosing a true physical cause and an effort directed to the mere observation of phenomena. A *vera causa* explains with equal facility the phenomena of every country and the observations of every age, whereas without it we can not correctly understand the commonest phenomena witnessed in our own time.

April 30, 1907.

FINAL NOTE.

Since the above discussion was completed, the writer has been much impressed with the excellent maps of the ocean depths published by the U. S. Coast and Geodetic Survey (Physical Hydrography, Manual of Tides, Part IV A, by Rollin A. Harris, Appendix 7, Report for 1900). The reader is requested to study especially maps 19 and 20, of this appendix, and to notice how the earthquake belts of the world as laid down by Milne follow the deep trenches in the sea. The borders of the North Pacific ocean, about Alaska, the Aleutian and Kurile Islands, and Japan are literally surrounded by these deep, narrow trenches, running right through the centres of the great earthquake belts of the globe. As these trenches are very long, narrow, and deep, and at the same time exactly paralleled by chains of islands rising out of the sea, which are mountain ranges under water, we see at once the true cause of earthquakes. The

expulsion of lava from under these trenches has raised the adjacent ridges, and when thus undermined the sea bottom has sunk down. This may be inferred with entire confidence and certainty not only from the relative situation of the trenches and adjacent ridges, but also from the great earthquakes and accompanying seismic sea waves observed in these regions within historical times. No other interpretation of the phenomena than the one we have given is really possible. If, however, any one should still cling to the old theory that the shrinkage of the earth is an effective cause in modifying the surface of our globe, let him explain why the shrinkage should take place in these long narrow trenches and be accompanied by the elevation of adjacent ridges. The elevation of the ridge shows that matter is pushed under it, and the sinking of the bed of the adjacent trench shows that the sea bottom is undermined. It therefore incontestably follows that lava is expelled from under the trench and pushed under the adjacent crust, upheaving it into the form of a ridge. Thus mountain ranges are formed in the sea and eventually raised above the water; and hence they run so exactly parallel to the shore. Earthquakes, volcanoes, mountain formation, formation of islands and plateaus, the feeble attraction of mountains, and great seismic sea waves,—six great classes of phenomena not heretofore closely associated,—are referred to one common cause, namely, the development of steam beneath the earth's crust, owing principally to the secular leakage of the ocean bottoms. The discovery and verification of this *vera causa* of the principal phenomena of the earth's surface ought to enable us to extend the domain of useful knowledge, and to give a better basis to many of the physical sciences.

BLUE RIDGE ON LOUTRE,

MONTGOMERY CITY, MISSOURI, July 2, 1907.

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THE NEW THEORY OF EARTHQUAKES AND MOUNTAIN FORMATION, AS ILLUSTRATED BY
PROCESSES NOW AT WORK IN
THE DEPTHS OF THE SEA.

BY T. J. J. SEE, A.M., LT.M., SC.M. (MISSOU.), A.M., PH.D. (BEROL.),
PROFESSOR OF MATHEMATICS, U. S. NAVY, IN CHARGE OF THE NAVAL
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(With Maps I.-III.)

By T. J. J. SEE, A.M., LT.M., SC.M. (MISSOURI), A.M., PH.D. (BEROL.),
PROFESSOR OF MATHEMATICS, U. S. NAVY, IN CHARGE OF THE NAVAL
OBSERVATORY, MARE ISLAND, CALIFORNIA.

(Read November 15, 1907.)

I. ON EARTHQUAKE PROCESSES OBSERVED IN THE DEPTHS OF
THE SEA.

§ I. *General Considerations.*—In two previous papers dealing respectively with the "Cause of Earthquakes" and the "Temperature of the Earth," a new theory has been developed which unites and harmonizes the most varied phenomena connected with the physics of the earth. These papers present the theory in a way which will no doubt seem convincing to the careful reader who has adequate experience in the physical sciences. But even the lay reader is entitled to all the light which may be shed on this difficult subject, and as the departure from previous theories is somewhat radical, it has seemed advisable to record some additional considerations which may be of interest also to the professional student of science.

This course seems the more appropriate in view of the established habits of thought of contemporary investigators, some of whom will naturally welcome any step which will simplify our understanding of physical phenomena. As the subject is extensive and complex and presented under various aspects in the different sciences, a connected view of the laws operating in the development of the earth's crust is by no means easy; for, if it were, the underlying cause no doubt would have been discovered long ago, and great improvements already would have been made in many of the physical sciences which deal with the terrestrial globe.

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Accordingly if we are able to give concrete and convincing illustrations of the processes now at work in the depths of the sea, they will prove the new theory beyond doubt for certain cases; and then Newton's rule of continuity can be invoked to show that a cause conclusively established in certain cases must be held to be general for all cases whatsoever, where the phenomena are similar. To prove the general physical cause of earthquakes, therefore, we need certain illustrations which admit of but one interpretation, and where there can be no possible doubt about the true nature of the process. If this can be established for a few typical cases we may feel sure that all world-shaking earthquakes and mountain-forming processes depend upon the same physical cause; and that the smaller earthquakes, which are very numerous, depend upon the larger ones and upon the gradual settlement of the crust where for any reason it has become unstable. To unite the small with the large earthquakes, in the hope of finding from the whole body of phenomena, when combined indiscriminately, their general cause, would be to labor in vain; for in the case of the large world-shaking earthquakes there is movement of molten rock beneath the earth's crust, while in the case of small earthquakes the tremors are due to a variety of causes, but more especially to any kind of instability which may give rise to a small movement of the ground. As the earth's crust is thick and the true nature of the underlying movement hidden from our view by the depth at which it occurs, the process involved can not be recognized without excluding from consideration the small earthquakes, and dealing exclusively with those great world-shaking disturbances, in which the effects are so large that the nature of the hidden process can be discovered. The disturbances which show the underlying process most clearly are beneath the oceans, or along the coast of deep seas, where there is expulsion of lava from beneath the sea under the land. We shall now consider some particular cases in which the meaning is unmistakable, and which have only been alluded to in the former papers.

§ 2. *The great earthquakes now occurring in the sea near the Aleutian Islands are developing a high submarine mountain range, of which only a few peaks rise above the water.*—It is generally

recognized by investigators that the most active region of seismic disturbances is along the Aleutian, Kurile, and Japanese Islands, and in the East Indies. Major Dutton not only speaks of the tremendous power of the mighty earthquakes in this region, but also calls attention to the prevalence of seismic sea waves following the earthquakes. "The profound depths of the ocean just off the eastern part of the Aleutian chain is one of the great breeding-grounds of world-shakers. A rather small basin in the ocean-bottom has here a depth of nearly four thousand fathoms, and the descent to it is by a long and strong gradient." ("Earthquakes in the Light of the New Seismology," p. 258.)

In the Bakerian Lecture to the Royal Society, 1906, Professor Milne treats of great earthquakes and says that "the most active district is at present that of the East Indies." But he also points out the great activity of the region along the Japanese and Aleutian Islands, where the sea is very deep.

Let us now examine the topographic map of the sea-bottom near the Aleutian Islands, as given in the Coast Survey Report for 1900, Appendix No. 7 ("Manual of Tides," Part IV., A, "Outlines of Tidal Theory," by Rollin A. Harris). We notice that along the Aleutian Islands the sea-bottom is sunk down into a narrow trough, which for a considerable distance is over 4,000 fathoms deep, and exactly parallel to the chain of islands. The length of this trough is found to be from thirty to thirty-three times its breadth; and the deeper part is only a continuation of the depression of the shallower. This is shown by the way in which the two troughs, with depths of 4,000 and 3,000 fathoms respectively, fit together, as if one were placed within the other. Moreover the chain of islands is seen to be merely the highest peaks of a mountain range rising just parallel to this deep trough. This range also is about 33 times longer than it is broad, so that if the elevation were shoveled off and thrown into the trough, it would just about fill up the depression, and leave the surrounding sea bottom of nearly uniform depth. By the same method of calculation which was employed in the paper on the cause of earthquakes (p. 311), it may be shown that the probability of this parallelism occurring without a physical basis is

only $1:(10)^n$, where we may put $n=33$. Thus the chances are only one in a decillion that this geometric parallelism would occur without a common underlying physical cause. The coincidence in volume is even more improbable, so that the agreement in direction and in volume, if depending wholly on accidental coincidence, would have a chance of only $1:(10)^{66}$, or one in a decillion decillions. A decillion decillions is practically an infinite number; and it therefore follows that the coincidence in direction and in volume depends on a true physical cause connecting the elevation of the range with the adjacent depression in the sea bottom.

Moreover, after great earthquakes in this region, new islands are frequently raised from the sea, and several new volcanoes have broken out within historical time. Seismic sea waves of the first class frequently follow, the water first withdrawing from the range of islands towards the trough to the south, and then returning later as a great wave. This shows that the sea bottom to the south sinks after the earthquakes by which the region is afflicted. As the islands, and in fact the whole mass of submarine mountains are uplifted by the disturbance, and the sea bottom afterwards sinks, it is evident that lava is expelled from beneath the trough and pushed under the adjacent range. The bed of the sea then gives down to fill up the partial cavity from which the molten rock has been expelled. It will be noticed, moreover, that the trough lies between the ocean and the mountain range, and hence if the leakage of the ocean were the cause of the expulsion of the lava, the subterranean movement necessarily would be towards the mountain range, in accordance with observation.

From this remarkable series of concurrent phenomena, it follows that the chances are literally infinity to one that the trough and ridge are physically connected. It thus becomes an absolute certainty that the submarine mountain range is formed by the expulsion of lava from beneath the trough, that the whole movement is due to the leakage of the ocean, and that it is going on right now; so that the effects observed within historical time are seen to be but a part of the secular process which has crumpled the earth's crust in this complicated manner.

A study of the map of North America shows that the Alaskan mountains to the north of Cook's Inlet are merely a continuation of the Rocky Mountains of Canada and the United States. The Alaskan mountains form the back bone of the Alaskan peninsula and continue into the sea as the Aleutian Islands. The Aleutian Islands are therefore part of the Rocky Mountains still beneath the ocean to show us how the whole system was formed in the course of immeasurable ages. What is here said about the Alaskan mountains running into the sea applies equally well to various other chains of mountains in different parts of the world.

Thus Mr. Caspar Wistar, formerly a student of Professor E. W. Brown, at Haverford College, now at Temuco, Chile, in sending the writer some valuable observations on the Andes, says: "The coast range begins properly about 25 miles north of Santiago, and there is no trouble in following it until it finally disappears in the ocean in Tierra del Fuego and Cape Horn. Lying between the coast range and the Andes is the central valley of Chile. At the northern end is the highest part, where it is close to 2000 feet above sea level; this gradually grows less as one goes south until finally at Puerta Montt it enters the ocean and can be followed on south below the sea level to Smyth's Channel and the western part of the Straits of Magellan."

In like manner the mountains of the peninsula of Lower California are continued under the sea; and dozens of other cases could be cited. These need not be dwelt upon here, as they are already sufficiently familiar to the reader. The case of the Aleutian Islands has been chosen for detailed study, because the mountain forming process is still actively at work there in a way which shows its real character.

The true process by which mountains are formed near the margin of the sea is thus recognized and placed beyond all doubt. Accordingly it follows that the old theories of mountain formation must be entirely abandoned, as having no valid foundation in nature. For owing to the similarity of the effects we cannot suppose that some mountains are formed by one process and some by another. All mountain ranges were near the sea originally, and essentially parallel to the shore; and since the mountains rear their lofty summits

about the sea, as serrated walls around the land, it follows incontrovertibly that all the mountains of the globe depend on the same cause, which is nothing else than the secular leakage of the ocean bottoms.

Reasoning similar to that here employed could be extended to the deep trenches near the Kurile and Japanese Islands; and by the study of the map of the ocean depths throughout the world one could tell very closely what the state of seismic activity is in any given region. No such digging out of troughs and elevation of adjacent ranges is found to be going on within any continent, and hence it follows that all mountain ranges have been formed by the sea and not at all by the shrinkage of the globe, which obviously is cooling as much in the desert regions as along the sea coasts.

§ 3. *Application of this Theory to Particular Regions of the Ocean Bottom.*—In view of what has been said above regarding the uplifting of ranges in the sea, is it any wonder that volcanoes should break out in the Aleutian Islands? Or, as Major Dutton remarks, that the Russians should connect the earthquakes with the volcanoes of this region? The connection is now established beyond all controversy, and it is shown that the earthquakes are the cause both of the volcanoes and of the mountain formation now going on in the Aleutian Islands.

In Japan the very same cause is at work, and the whole island Empire has been uplifted from the depths of the sea by the injection of lava expelled from beneath the bed of the Tuscarora Deep, which has thus sunk down and developed into the greatest abyss in the world. The true cause of the earthquakes and sea waves by which Japan is afflicted lies in the depth of the ocean to the east of these islands and the resulting leakage and expulsion of lava from beneath it. As the ocean is deepening all the time, this region will always be greatly afflicted by seismic disturbances, and the Japanese people must adapt themselves to the nature of their unstable country, which is still emerging from the depths of the ocean.

It is easy to apply this same reasoning to the East Indies, and hence we see why Java, Sumatra, and other neighboring islands are so afflicted by earthquakes, volcanoes, and seismic sea waves. This region probably is in a more advanced stage of development



than that of the Aleutian Islands. The latter will eventually connect North America with Asia, and the Arctic will be entirely cut off from the Pacific Ocean. Thus by the study of maps of the ocean depths much light can be thrown upon the past history and present tendencies of the surface of our globe. Even now we may see the formation of islands, mountains and borders of continents still going on. Not only is mountain formation and the uplift of islands going on near the margins of the sea, but, also, at considerable distance from the continents, towards the interior of certain oceans. As a good illustration of this interior development we choose the region of the Friendly Islands in the Pacific between Samoa and New Zealand. Here the water is very deep and the narrow trench is built exactly like that near the Aleutian Islands, having on the west a ridge which has been uplifted by the injection of lava from beneath the trough to the east. The Pacific is here developing a long mountain wall on the west, and it will eventually connect Samoa with New Zealand. The earthquakes and seismic sea waves observed in this region show that the process is going on now, and slowly developing a chain of mountains in the open sea, at some distance from any large continent.

§ 4. *On the Development of Islands and Island Chains.*—In view of the above considerations, it is clear that small islands are essentially mountains under water; and that in the case of large islands the uplifted area was larger, and the bases have since been broadened by the elevation of more land, and the tops flattened by the agencies of wind and water. This was pointed out in the first paper on the cause of earthquakes, §§ 30–38, and attention was called to the lay of the mountains along the centers of the islands, and to the depressions in the bed of the ocean near many of them, due to the sinking of the sea bottom, after the crust was undermined in the process of elevation. By a continuation of the process almost any amount of land could be added. When the uplifted area is of considerable extent, the resulting islands are large, and have flat tops, partly owing to the secular effects of such agencies as wind, water and the leveling action of the waves. Whenever we see a chain of islands in the sea, we know that they are essentially the peaks of a moun-

tain range elevated above the water. A case such as that offered by the Aleutian Islands proves this beyond all doubt; yet in most cases the process of formation has been slow, and the present state of the sea bottom does not show exactly how the development came about. From the study of those islands near which depressions exist we may in time gather much light on the details of island development, and in this way add to our knowledge of the geology of the sea. While the illustrations already given show the general nature of the process, it is clear that the sea bottom is still too little explored to enable us to treat of all cases intelligently, and we must therefore wait for more light as the surveys of the oceans are gradually extended. It is obvious that exact surveys of the sea bottom are needed not only for the laying of cables, but also for the study of the earth's geological history; and the time may come when exact ocean surveys may be as important for our knowledge of the physics of the earth as geological or geodetic surveys of the land.

§ 5. *On the Nature of the Molten Rock Which Moves Beneath the Earth's Crust.*—In the paper on the Cause of Earthquakes we have pointed out the leaky character of the earth's crust, and shown how steam will naturally form in the hot rocks beneath till the lava becomes so fully saturated by this vapor that it swells and requires more space. The steam is not held to be free, but absorbed in the hot rock, causing it finally to expand till it becomes irresistible; and when the elastic tension of this steam-saturated lava becomes great enough the crust begins to shake and the paroxysm continues till it moves along the nearest fault line. When the underlying molten rock has thus obtained more space, the agitation ceases till the tension again becomes too powerful for the crust to withstand, when another readjustment will take place. Thus the process is repeated at successive somewhat irregular intervals of time. The shaking is due to the enforced movement of the molten rock beneath the crust, and the paroxysm thus developed sometimes shakes down cities and devastates whole countries.

A familiar illustration of this process is seen in the lid of a tea-kettle when the steam pressure accumulates till it sets the lid quivering; as the steam escapes at the sides the agitation slowly dies down,

and the lid then remains quiescent till the accumulating pressure again requires relief, when the shaking is renewed. Thus the process is periodic, and the period depends on the rapidity with which the steam is developed. In the case of earthquakes, as already remarked, the steam is not free, but absorbed in the molten rock, and when the agitation begins this gives a similar quivering motion to the block of the earth's crust overlying it, and ceases only when readjustment occurs, usually by the neighboring fault slipping in some way to give more space to the swelling lava beneath. The period is not so regular, as in the case of the tea-kettle, because the resistance to be overcome is never the same in two successive earthquakes; nor is an equal amount of relief afforded even when the underlying force is identical, because the crust moves as soon as its resistance is overcome, and it ceases to move when the displacement is sufficient to restore equilibrium. As the resistances to the blocks of the earth's crust are constantly varying, owing to their complicated mutual relations, and the steam also accumulates at various rates and unequally under different parts, the intervals between successive shocks may be approximately, but are never exactly, equal. Settlements after great shocks, and slight stresses, are relieved by small movements, but eventually the tension becomes great enough to demand a displacement that will provide more space beneath the crust, and then the resulting fault movement usually is conspicuous enough to show at the surface of the ground. The crust is about fifteen or twenty miles thick, and molten lava seldom reaches the surface, except when the crust is uplifted and an outlet facilitated by the opening of cracks, as in mountain chains, which may be along the shore, or in the depths of the sea, projecting above the water as islands. Hence not all islands are volcanic; and by no means all mountains become volcanoes; but such out-breaks frequently happen in the neighborhood of deep seas, where the expulsion from beneath the sea is most violent, and the crust is abruptly and sharply upheaved, so as to afford a chance vent for the imprisoned vapor.

§ 6. *The molten rock beneath the oceans probably experiences an enforced creep towards all available avenues of escape, but the movement usually is not rapid enough to prevent the bottom from*

sinking where the undermining due to expulsion is very active.— This may be inferred from the fact that an ocean such as the Pacific is surrounded everywhere by high mountains, and often by table lands of great elevation. All these mountains and plateaus have been raised from the sea, by injections of lava expelled from beneath the bed of the ocean. The fact, however, that in many places, as along the Aleutian, Kurile, Japanese, and East Indian islands, South America, and elsewhere, the expulsion of lava has been so rapid as to dig out trenches near the ranges of mountains thus elevated, leads one to recognize that in some places the expulsion towards the land is more rapid than the creep of lava from under the sea towards the shore, so that the sea bottom sinks down into a trough. This expulsion of lava happens in a good many places, and the phenomena are clear enough to admit of no doubt. Yet it seems certain that some lava creeps under the crust towards all avenues of escape, along the paths of least resistance, and enforced movements occur in submarine earthquakes. Islands are thus raised in the sea, and where the undermining is rapid the adjacent sea bottom sinks down. Sometimes large plateaus form in the ocean, and slowly rise to the surface, so as to form a large flat island, generally of an elongated type. Submarine plateaus of this kind are now to be found in the north and south Atlantic, and elsewhere, and there can be scarcely any doubt that the leakage of the ocean finds relief by the gradual elevation of such submarine masses, as well as along the shores. The effect of this process is to augment the corrugation of the earth's crust in the course of geological time; and eventually the highest mountains in such submarine ridges rise above the water as islands. On October 16, 1907, a very powerful earthquake was felt all over the world, and the seismographic records located it in the Pacific Ocean between Mexico and Hawaii, about 1,000 miles south of San Francisco. This earthquake seems to have been purely submarine, and even more powerful than those which devastated San Francisco and Valparaiso. It is by such submarine movements that the sea bottom is constantly disturbed and corrugated and crumpled in a thousand ways, and some of the elevations are eventually lifted above the water as islands.

§ 7. *The Effects of Pressure upon the Penetration of Water into the Earth's Crust.*—To judge how effective the pressure arising from the depth of the ocean is in driving the water into the crust of the earth, we may observe first that as water is nearly incompressible for moderate pressures, the tendency to penetrate the rocks is everywhere proportional to the depth of the sea. Thus the deeper the water the greater the pressure and penetrating power. Consequently it is chiefly in the deepest water that we should expect to find the maximum effect arising from the secular leakage of the ocean bottoms. In water of any given depth the pressure is theoretically sufficient to throw a free jet to the surface, if the stream could be made to operate in a vacuum. The pressure in a sea one mile deep would thus throw a stream a mile high; in a sea two miles deep, two miles high; and so on. Now some of the ocean depths exceed five miles, the greatest, near Guam, being 5,269 fathoms, almost exactly six miles. Is it therefore any wonder that the deeps east of Japan, near the Aleutian Island, west of South America, near Guam, between Samoa and New Zealand, give rise to enormous leakage of the sea bottom, and consequently many world-shaking earthquakes? A comparatively feeble pressure of water, such as hydraulic engineers use in mining, rapidly cuts away hills and washes out all their gold; in the same way the waters of Niagara, falling through only 160 feet, slowly wear away the solid rock over which they pour.* What then may be expected of a constant water pressure which will throw a jet five miles high? Such is the pressure all over the bed of the Tuscarora Deep, and it continues from year to year, century to century. It is this pressure which forces the water so rapidly into the earth, and gives rise to all the great earthquakes and sea waves with which Japan is afflicted. No stone on earth, however thick its layers, could withstand such a pressure; nay, under it the water would go through the hardest metals, and sink down deeper and deeper into the bowels

* This analogy with the hydraulic effects of streams of water in motion is not perfect, for the water in the deep seas is merely subjected to great pressure, without bodily movement; yet in both cases the water penetrates the stone to a certain depth. In the one case the water keeps on descending into the earth, in the other the surface particles are carried away by the moving stream.

of the earth. Thus subterranean steam would arise beneath the crust and accumulate till relief was afforded by a shaking of the earth, which gave more space for the saturated underlying molten rock. Hence arise the earthquake belts near the deep seas, where easy relief becomes established in the neighboring crust as it is gradually uplifted into a great ridge or mountain chain.

§ 8. *Explanation of the Instability of Steep Slopes near Deep Seas Noticed by Seismologists.*—Montessus de Ballore and Professor Milne both dwell on the instability of steep slopes near deep seas. The meaning of this is now plain; namely, the slopes become steep by the uplifts due to the expulsion of lava from beneath the deep seas, and the seismic instability arises from this expulsion of lava under the land. The converse proposition for shallow seas is obvious enough, and well illustrated almost all over the world. In some places relief goes on after the seas have become shallow, but there can be scarcely any doubt that the movement started when the water was deeper than it is now. *The world as we find it represents the cumulative effects of physical causes working over vast periods of geological time. And our best rule is to study the typical processes where the water is deep, and the undermining and upheaval so plain as to admit of no doubt. In time we may be able to trace out the history of other unstable regions now in shallow water, or even above the sea level.* No one would now expect to see a range of mountains form far inland, and where such ranges now stand the bed of the sea once encroached. In the course of time the details in the development of such ranges will no doubt be fully worked out, but geology is not yet sufficiently advanced to unravel all that is hidden in the crumpling and folding of the earth's crust. The progress of the next two centuries ought to enable us to write a fairly accurate history of the development of the earth. All the details of particular regions now being gathered would be unintelligible unless analyzed by means of correct underlying principles, and as these have only been established very recently, we content ourselves with outlining correct general ideas, and illustrating the true physical cause by a few cases which are beyond question. More cases can be added when our knowledge of the world is more developed; but it may require the work of several

centuries to bring out this complex development for all the principal regions of the globe.

II. CAUSES OTHER THAN THE SECULAR LEAKAGE OF THE OCEAN BOTTOM.

§ 9. *The presence of mountain forming processes in the sea, and the absence of such disturbances in the interior of continents excludes the consideration of secular cooling as an active cause in the modification of the earth's crust.*—In the paper on the temperature of the earth we have seen that secular cooling is a very slow and gradual process; and, moreover, it would necessarily operate as effectively for inland as along the sea coasts. Consequently if this cause were real, it ought to produce effects inland comparable to those along the edges of the continents; but the mountains are forming in the sea, and those already completed are distributed along the sea coasts; so that no one would think of ranges now being developed in an interior region far from the oceans. The absence of such mountain-forming processes in the interior of the continents therefore excludes secular cooling as an active agency in the modification of the earth's crust. *The effects of secular cooling could in no case exceed the disturbances noticed in the inland regions, and as these are insensible in regions free from water, it follows that secular cooling is not a true physical cause of mountain formation and kindred phenomena. Consequently this cause is not now and never has been active in modifying the crust of our globe.*

§ 10. *The Untenability of the Theory that World-Shaking Earthquakes Arise from the Snapping and Bending of Rocks.*—In view of what has been established in this series of papers, it is difficult to see how any one could again ascribe world-shaking earthquakes to the bending and snapping of rocks under stresses arising from the progress of secular cooling. If this is the cause which is at work, why should the great seismic disturbances occur chiefly in or near the oceans, and especially where the sea is deep, while inland regions remain quiescent? By no possible stretch of the imagination can these movements be traced to the secular cooling

of the terrestrial globe. For, if so, how are we to explain the digging out of ocean trenches and the elevation of the adjacent crust into a mountain range, as often happens in the depths of the sea? If any kind of wrinkling due to secular cooling were at work, it seems certain that the inland regions could not escape the same influence.

The difficulty experienced in accounting for the vibrations of the great earthquake at San Francisco, on the hypothesis that a rock had snapped or slipped, is thus fully sustained. If such a cause had given rise to the earthquake, the vibrations would have been of simpler character, accompanied by less rotatory motion, and the whole disturbance would have been less violent and of much shorter duration. It may be asserted with confidence that no vibrations arising from the snapping of rocks would have been sufficiently powerful or long continued to shake down cities and spread universal devastation over the land. Above all, such effects of secular cooling could not explain a general phenomenon like the uplifting of the mountains as veritable walls about the margins of the sea. Nothing but the expulsion of lava from under the sea would be adequate to account for this upheaval of the crust, and it is hard to see how any thing but the shaking incident to this enforced and prolonged subterranean movement could devastate the land and disturb the whole world. In the expulsion of lava from beneath the sea, the true cause of earthquakes is clearly recognized, and all the most important phenomena connected with the physics of the globe are correctly assigned to the secular leakage of the ocean bottoms, which necessarily is greatest where the sea is deepest. This hypothesis alone is adequate to account for all the phenomena of nature. The unity and harmony and mutual dependence shown to exist among the most diverse phenomena observed at the surface of the earth is the best proof of a common underlying cause, and such a theory will strongly commend itself to the natural philosopher who seeks in the abundance and variety of nature indications of a single fundamental law.

How great is the change in the new point of view may be seen from the following discussion by Professor J. W. Gregory, taken from the "London Sunday at Home," 1906:

"A volcano is a pin-prick in the earth's surface and it serves to relieve the local pressure by permitting the escape of steam and molten rock; but an earthquake is produced in most cases by a sudden fracture of the solid substructure of a large region, and as the great mass of material slips into a new position, the shock causes the crust of the earth to shiver from pole to pole. These dislocations are naturally most frequent in regions where mountain ranges are apparently still being squeezed up—where rocky folds are still being bent into shape, as in the Himalayas, and off the west coast of North and South America, and the North of Japan. Regions of greatest instability of the earth's crust are, in fact, found chiefly along the margins of continents or tablelands which rise suddenly to considerable heights above oceanic or other plains. Comparatively few earthquakes have their origin near to volcanoes, and the general belief that all great earthquakes are due to volcanic eruptions is not supported by evidence derived from observations."

Professor Gregory thus says that earthquakes occur chiefly where mountain formation is in progress, but he is entirely silent as to the cause of mountain formation itself. Unfortunately he blindly accepts the traditional doctrine of the secular cooling and contraction of the globe, which is shown to be devoid of any sound physical basis.

§ 11. *An Estimate of the Relationship between the Expansion and Contraction of the Globe.*—It is well known that at intervals the sea coasts are elevated by the world-shaking earthquakes to which they are subjected. It is difficult to form an estimate of the total area thus uplifted, but for a preliminary estimate we may take it to have an average extent of 200 miles square, which would about correspond to the phenomena witnessed in the greatest earthquakes. There would be 4,924, or roughly 5,000, such areas on the surface of the entire globe. According to Milne's estimate of 60 world-shaking earthquakes per annum, there would be 120,000 in the 2,000 years which have elapsed since the century before the beginning of our era.

Now an examination of great earthquakes shows that about one in four is accompanied by a sensible elevation of the disturbed area. If there are in all 5,000 such areas to raise, and 30,000 disturbances for raising them, it follows that on the average, when all areas are affected alike, each part would be raised 6 times in 2,000 years. An average raise of 2 feet is not extreme, and this gives an expansion of the total surface of the globe amounting

to 12 feet in this period. In the paper on the temperature of the earth, p. 286, we have shown that the shrinkage due to cooling in 10 million years, according to Daniell, would not exceed 612 feet; and, taking this effect to be uniform, the shrinkage in 2,000 years would be only 0.12 of a foot, or exactly 0.01 part of the calculated elevation due to earthquakes. Now in the above calculation of the expansion due to earthquakes, we may have taken the disturbed area too large; but one uplift in four great disturbances does not seem to be an over estimation of the effects of elevation. The sinking of the sea bottom, however, goes on, and less frequently the land along the shore is carried down also; and possibly the elevation is relatively less than we have computed. As this calculated expansion is 100 times the shrinkage, we might reduce the size of the uplifted areas to 100 miles square, and still the expansion would exceed the contraction by 25 times. We could again reduce the areas to 50 miles square and make the uplift over 6 times the contraction. If, however, the uplifts be restricted to the areas covered by the land, the effect would be quadrupled. To make the expansion just equal to the contraction we should have to reduce the amount of the average vertical uplifts from 2 feet to 1 inch, or make the 2-foot uplifts 24 times less frequent, so that only one would occur in 96 great earthquakes.

This seems to be excessively small, and I think it practically certain that the expansion of the globe is from 10 to 100 times more rapid than the contraction, in the evaluation of which we have used Daniell's maximum estimate.

When we contemplate the mountains and plateaus, we see that an expansion of our globe is indicated by its general aspects. For it is in this manner that the mighty mountains have been upraised, and the vast plateaus uplifted, without greatly depressing large areas of the sea bottom. As the earth is almost totally devoid of shrinkage due to secular cooling, the maximum estimate being 1.44 inches in 2,000 years, this most probably indicates a secular expansion of our planet. In any given age the expansion is not equally effective all over the terrestrial spheroid, but the present distance of many mountains and plateaus from the sea shows that

it goes on steadily, and in times gives rise to large effects over considerable belts. It seems therefore practically impossible to avoid the conclusion that our earth is not contracting at all, but on the contrary is actually undergoing a slow secular expansion. In any given geological age the areas uplifted may be confined to particular regions, chiefly along the sea coasts, but in the long run it will include a large part of the earth's surface. In the course of ages more and more land is raised above the sea, which at the same time is contracting its extent and decreasing its total volume by the secular desiccation arising from the gradual absorption of the waters into the rocks of the earth.

§ 12. *Researches Founded on the Hypothesis of the Gravitational Instability of the Terrestrial Spheroid Rest on a False Premise.*—

Quite recently several of the most learned mathematicians in England have treated of the uplift of the continents and their secular movements, on the hypothesis that these effects are due to gravitational instability in the progressive shrinkage of our planet. It is scarcely necessary to point out that in order to reach correct conclusions we must start from correct premises, as well as follow an unbroken chain of reasoning. One may readily concede that the learned discussions which have appeared from several eminent investigators are perfect specimens of the logical art, and adorned with flawless mathematics. But if the premises are not well founded in nature, the superstructure built thereupon necessarily falls to the ground. It does not seem to have occurred to these learned investigators to examine critically the underlying premises, for no doubt they assumed the historical doctrine of secular cooling and contraction of the globe as unassailable.

From our study of this question, however, it seems certain that the earth's cooling is infinitely slow, and that no sensible contraction or other movements depend on this cause. The observed movements are always near the sea, which shows that they depend in some way upon the oceans. As the land is frequently upheaved along the sea coast, and all the mountains and plateaus have been thus uplifted, it is impossible for such movements to depend upon the mere settlement of a gravitationally unstable planet. Hence in the present en-

crusted state of the earth we must reject the whole doctrine of secular shrinkage as false and misleading.

As the earth was once of larger volume and smaller density than at present, there may have been a time when it was settling owing to gravitational instability, *but this was long before the surface had become encrusted*. Since the consolidation began the cooling has been excessively slow, and no convective circulation has taken place within; consequently the planet has not since experienced any sensible gravitational instability, except that due to earthquakes arising from the penetration of water vapor, which gives rise to mountain formation and kindred phenomena now witnessed at the surface of the earth. The theory of gravitational instability as applied to the earth therefore is not valid, because it applies to a far earlier stage in our history, before the crust had begun to form. The premise underlying this learned reasoning seems therefore false, and we can only look upon such an ingenious speculation as an interesting example of brilliant abstract reasoning, in no way applicable to the present or recent history of our planet. By no possibility could such theories enable us to explain the distribution of earthquakes, or their prevalence near deep seas, where trenches are being dug out in the sea bottom and mountains uplifted along the borders of these abysses.

What is said here in regard to these several investigations applies also to Professor Love's learned discussion of the gravitational instability of the earth, involving the various orders of spherical harmonics. His beautiful mathematical theory is a monument of ingenuity, correct on the hypothesis, but the latter is lacking in physical basis, and consequently the investigation is chiefly valuable as a piece of abstract reasoning of high order, interesting in dynamics, but not applicable to the development of our actual earth.

§ 13. *Views of the Late Professor James D. Dana on Mountain Formation.*—Among the many eminent geologists who have treated of mountain formation, the late Professor James D. Dana stands preëminent for having come nearest to the correct theory; and although the false hypothesis of the contraction of the earth underlies his views and vitiates them, yet they are sufficiently remarkable

to deserve the attention of the careful reader who seeks to follow the historical development of human thought. It is only by a survey of this kind that one gets an adequate perspective of the theories developed in the different ages. Dana's views are given in his "Manual of Geology," 1863, and the most interesting passages are the following:

(A). On page 29, he points out that the continents are all walled in by mountains erected about their borders, and adds:

(a) "The continents thus exemplify the law laid down, and not merely as to high borders around a depressed interior—a principle stated by many geographers—but also as to the highest border being on the side of the greatest ocean (first announced in *American Jour. Sci.* (2) XVII, vols. III, IV, 1847, and XXII, 335, 1856). The continents then are all built on one model, and in their structure and origin have a relation to the oceans that is of fundamental importance."

He also observes that the borders of continents are from 500 to 1,000 miles wide, and infers that "a continent can not be less than a thousand miles (twice five hundred) in width," otherwise it would not have the characteristic basin form with mountain barriers about a low interior.

(b) On page 731 he discusses the evolution of the earth's great outline and reliefs, and of the successive phases in its progress, summarizing his conclusions as follows:

I. "The continents have mountains along their borders, while the interior is relatively low; and these border mountain chains often consist of two or three ranges elevated at different epochs."

II. "The highest mountain-border faces the largest ocean, and conversely."

III. "The continents have their volcanoes mainly on their borders, the interior being almost wholly without them, although they were largely covered with salt water from the Azoic age to the Tertiary. Also metamorphic rocks later than the Azoic age are most prevalent near the borders."

IV. "Nearly all of the volcanoes of a continent are on the border which faces the largest ocean."

V. "The strata of the continental borders are for the most part plicated on a grand scale, while those of the interior are relatively but little disturbed."

VI. "The successive changes of level on coasts, even from the Azoic age to the Tertiary, have been in general parallel to the borders of mountain chains; as those of the eastern United States, parallel to the Appalachians, and those of the Pacific side, as far as now appears, parallel to the Rocky Mountains."

VIII. "The continents and oceans had their general outline or form defined in earliest time. This has been proved with regard to North America from the position and distribution of the first beds of the Lower Silurian—those of the Potsdam epoch. The facts indicate that the continent of North America had its surface near tide-level, part above and part below it (p. 196), and this will probably be proved to be the conditions in Primordial time of the other continents also. And, if the outlines of the continents were marked out, it follows that the outlines of the oceans were no less so."

The three other conclusions announced by Dana are of less interest, and need not be quoted here.

(B). The following deductions (p. 732) regarding the positions of the reliefs are of high interest:

"1. The situation of the great mountain chains, mainly near the borders of the continents, does not indicate whether the elevating pressure acted within the continental or oceanic part of the earth's crust. But the occurrence between the principal range and the seacoast of the larger part of the volcanoes (and, therefore, of the profound and widely-opened fractures) of these borders, of the most extensive metamorphic areas, and of the closest and most numerous plications of the strata, as so well shown in North America, are sufficient evidence that the force acted most strongly from the oceanic direction."

"2. The relation between the extent of the oceans and the height and volcanic action, etc., of their borders proves that the amount of force in action had some relation to the size and depth of the oceanic basin. The Pacific exhibits its greatness in the lofty mountains and volcanoes which begirt it."

"3. In such a movement, elevation in one part supposes necessarily subsidence in another; and, while the continental was the part of the crust which was elevated, the oceanic was the subsiding part."

In connection with the theory that the mountains are formed by the expulsion of lava from beneath the sea, through the operation of world-shaking earthquakes, these early views of Dana are of great interest. But in other respects he was led astray by the doctrine of the secular refrigeration of the globe; for he says that "no other cause presents itself that can comprehend in its action the whole globe and all time." He thus speaks as if the entire globe were shrinking, whereas local changes only are occurring, and these always near the sea. Dana's view that "the pressure of the subsiding oceanic portion has acted against the resisting mass of the continents; and thus the border between them has become elevated, plicated, metamorphosed and embossed with volcanoes," is alike

misleading and unjustifiable. For to produce such an effect the settling of the ocean basin would have to be many miles, and we have shown that no such shrinkage has taken place since the crust was formed; on the contrary there is reason to think that the earth is expanding at a rate of from 10 to 100 times that of the contraction due to secular cooling. Moreover we have no more right to assume that the continent is squeezed by the settling of the ocean, than that the ocean is squeezed by the settling of the continent.

We have, however, recalled these views in order to do justice to the most original of the older American geologists, and also to let the student see where he departs from the true line of thought. Many years ago Rev. O. Fisher showed that shrinkage was wholly inadequate to account for the height of the mountains observed upon the earth, which are hundreds of times higher than the contraction theory will explain. In the paper on the cause of earthquakes it is shown that the contraction theory is also emphatically contradicted by the present distribution of mountains. In the present paper and that "On the Temperature, Secular Cooling and Contraction of the Earth, and on the Theory of Earthquakes held by the Ancients," it appears that at present the earth is not contracting at all; so that we are compelled to abandon the older theories entirely.

As heretofore developed geology has presented the strange anomaly of offering no theories adequate to account for the uplift of mountains and plateaus or the deposits of fossil beds thousands of feet above the sea. This is the more remarkable, since in the days of Humboldt, Lyell, and Darwin, the bodily elevation of the land was an accepted item of belief. But subsequently Lord Kelvin, Sir George Darwin, and other eminent British physicists, showed, from the investigation of tidal and other phenomena, that the earth as a whole behaves as a solid; and under the influence of this line of thought geologists gave up the doctrine of the bodily elevation of the land, and restricted themselves to the collapse of portions of the crust under gravity. The theory of collapse, however, utterly fails to explain mountains and plateaus and islands, as well as shells and other organic remains at great height above the sea level. But it was felt that the argument of the physicists against the bodily

yielding of the earth was unanswerable, and so it is for the globe as a whole; yet this does not disprove the existence of a layer just beneath the crust which in earthquakes behaves as fluid*

In the present researches a theory is developed by which these two views may be reconciled, and it is, I think, clearly proved that in earthquakes there is movement of molten rock beneath the earth's crust. It is this movement of molten rock beneath the crust which produces most of the dislocations, crumpling, folding, and fault phenomena studied in geology. If such a theory is justifiable, it shows us how cautious we must be in drawing final conclusions, and how incomplete all the sciences still are to-day.

§ 14. *Criticisms of the Theory here Adopted.*—Not many criticisms of weight have reached the writer since the publication of the papers on the "Cause of Earthquakes" and the "Temperature of the Earth," but he may here notice two to which some attention may be given.

1. *A geologist thinks that the absence of volcanoes about the South Atlantic is difficult to explain.* This supposed difficulty is much less real than it seems; for some submarine volcanoes have been known in that region, and a good many submarine earthquakes. The sea is shallow near the borders, but a long tableland is rising in the center, and we have no means of knowing how many disturbances occur in this region, which is comparatively seldom visited by ships. Probably the lava finds an avenue of escape under this submarine plateau, and some sea waves occur from time to time, but the region is too far from land to produce great inundations of the shore. As the land is not yet lifted into a sharp ridge, the mountains do not yet appear above the water, and such eruptions as occur beneath the

* Since this was written Professor Wiechert of Göttingen has presented to the International Seismological Association in session at the Hague, Sept. 21-26, 1907, a report of the chief results of his researches on the internal constitution of the earth. The existence of long vibrations in the tremors propagated by earthquakes, with periods of eighteen seconds or more, reveals, he thinks, the presence of a layer of liquid or plastic material at a depth of about thirty kilometers from the surface. (See report of meeting by Professor Harry Fielding Reid in *Science*, Jan. 10, 1908.) Note added Jan. 22, 1908.

sea pass unnoticed. It is not remarkable, therefore, that we find so few volcanoes in this region, and the absence of known volcanoes in no way contradicts the theory. Volcanoes usually break out after mountain ridges are folded sharply upward; this stage may come later in the South Atlantic, where the sea is neither very deep nor the gradient very steep near the shores. Consequently in such a region we should not expect at present many volcanoes or great visible earthquake effects.

2. *Some geologists have believed also that the steam escaping from volcanoes comes from the central magma of the globe.* But if this were true, as we have pointed out in the paper on the "Temperature of the Earth" (p. 288), the volcanic outbreaks ought to occur in the interior of the continents as well as near the oceans. For the vapor ascending from the central magma of the globe could not always be deflected around the immense extent of the continents, and appear only at their edges, and in the depths of the sea. The geographical distribution of volcanoes therefore effectively contradicts any such hypothesis.

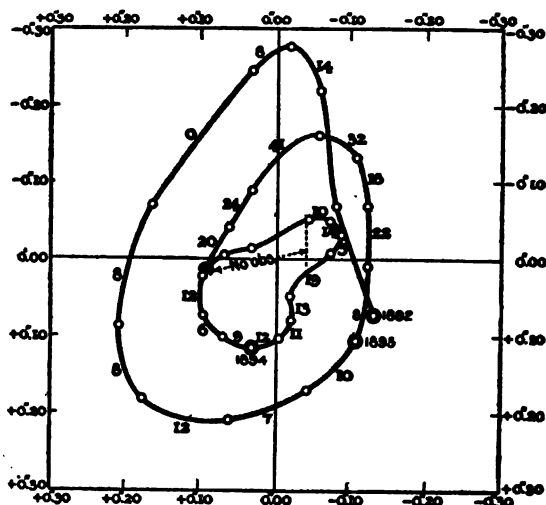
§ 15. *The Criticism based on the Supposed Coincidence of Great Earthquakes with the Sudden Shifting of the Earth's Axis in its Revolution about the Mean Axis of Figure.*—A reviewer of the paper on the "Cause of Earthquakes," in *Nature*, August 1, 1907, after admitting the adequacy of the cause assigned to explain most phenomena finally adds:

"But his (See's) explanation fails to account for the remarkable connection between the irregular shifting of the earth's axis and the occurrence of the greatest earthquakes. That these irregular movements of the axis are greatest when large earthquakes are most frequent is a certain, but as yet unexplained, fact; it seems to necessitate displacement of matter in the earth on a far larger scale than is indicated by the differential measurements which alone are open to us. Professor See's explanation, though it provides for lateral and vertical displacement of matter, necessitates the elevations and depressions being so closely contiguous as practically to neutralize each other's effects, and, therefore, fails as an explanation of the ultimate cause of earthquakes, while it in no way affects the current acceptance of fracture as their immediate cause."

This criticism is not well founded, and after what has been said above and in the two preceding papers, probably does not require

any elaborate notice; yet we may briefly point out the weakness of the position taken, which seems to be the same as that announced by Professor Milne in his Bakerian Lecture to the Royal Society, 1906, where he says:

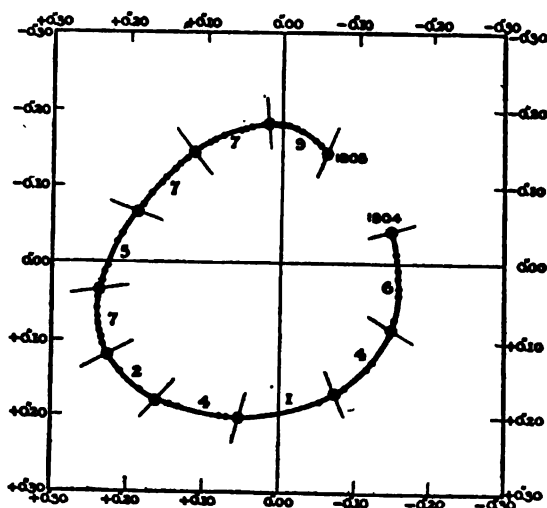
"If we take a chart showing the varying position of our earth's north pole in relation to its mean position, we see that the secular movement of the pole is by no means uniform. Although it may at times follow a path about its mean position which is approximately circular, at other times there are comparatively sharp changes in direction of motion which may even become retrograde. If now on a chart of this description we mark the time positions of very large earthquakes, we find that they cluster around the sharper bends of the pole path." (See the accompanying figures with explanations taken from Professor Milne's paper.)



"FIG. 1. After Th. Albrecht. The path of the North Pole from 1892 to 1894 inclusive. Each year is divided into tenths or periods of 36.5 days. Numerals indicate the number of large earthquakes which occurred in each of these divisions, commencing with the third tenth of 1892."

"In a period of nearly 13 years (1892 to 1904) I find records for at least 750 world-shaking earthquakes, which may be referred to three periods continuous with each other, and each two tenths of a year or 73 days' duration. The first period occurs when the pole movement followed an approximately straight line or curve of large radius, the second equal period when it was undergoing deflection or following a path of short radius, and the third when the movement was similar to that of the first period. The numbers of earthquakes in each of these periods taken in the order named were

211, 307 and 232, that is to say, during the period when the change in direction of motion has been comparatively rapid, the relief of seismic strain has not only been marked, but it has been localized along the junctions of land blocks and land plains where we should expect to find that the effect of general disturbances was at a maximum. It can hardly be assumed that the



"FIG. 2. This is similar to Fig. 1, but refers to the year 1903, during which period the pole displacement was more uniform than that indicated in Fig. 1."

frequency under consideration is directly connected with change in direction of pole movement; but it seems not unlikely that both effects may arise from the same redistribution of surface material by ocean currents and meteorological causes generally."

This reasoning of Milne asserts that the greatest earthquakes occur when the path of the pole bends most rapidly. In reply to this claim we may remark in the first place that it is very doubtful whether a general law of this kind can be fairly deduced from existing observations, because the path of the pole depends on such minute quantities that the curvatures platted may not be real. In the second place, if the assumed law were admitted, the meaning of it would still be open to interpretation, and several of these could no doubt be made without involving a contradiction of known laws.

For the total displacement of the pole from the mean position is nearly always less than 30 feet, and generally less than 15 feet;

these movements correspond to quantities represented in arc by $0''.30$ and $0''.15$, which are on the very limits of our most accurate astronomical measurements. The apparently sharp turns in the pole path, therefore, may not be real, but merely a delusion arising from some unknown cause. If, however, these sharp turns are real, this fact cannot be certainly established till the polar motion has been repeated many times, and the data now available do not seem sufficient for this purpose.

Moreover, even if the sharp turns are real and it could be proved that the great earthquakes gathered about them, in regard to which there is still much doubt, our interpretation of the results would be open to much uncertainty. For it could not be inferred that large masses of matter are in motion within the earth, and that the displacement of these masses causes a sudden change in the movement of the pole. We have seen that the matter of the earth's interior is kept rigid by pressure, and that no movement deep down in the globe ever takes place. This is shown by the fact that a shock originating deep down would be felt with moderately uniform intensity over a large area, which is disproved by observations showing that all great earthquakes are quite superficial. If no shocks originate at great depth, the only other possible movement would be just beneath the crust; and it is quite impossible that currents could move for great distances just beneath the surface without disturbing the whole intervening region of the globe.

Much as has been done on this difficult subject by the greatest mathematicians, it is not yet known what causes operate to displace the pole from the mean axis of figure, and maintain the displacement in spite of friction and viscosity; but recurring seasonal effects, together with the imperfect rigidity of the earth, have been generally accepted as the chief causes. Is it not, therefore, probable that whatever displaces the pole and thus maintains its revolution about the mean pole, according to the Eulerian Theory as modified by viscosity and imperfect rigidity, may suffer variations through combinations of storms, and other atmospheric and tidal agencies? And that these combinations of varying stresses operate to bring on earthquakes where instability of the crust already exists, from the accumulation of subterranean steam pressure?

These combinations of circumstances are not the dynamical *cause* of the earthquakes, but only the *occasion* for outbreaks when instability is already developed. It might thus be that earthquakes would break out when the polar motion is changing most rapidly, *but the earthquakes do not cause the change; rather they are occasioned by that which makes the change.* Milne's view above quoted does not seem to differ much from this, for he says that "both effects may arise from the same redistribution of surface material by ocean currents and meteorological causes generally," though he overlooks the leakage of the oceans as the cumulative dynamical cause of instability.

On these grounds probably very few will agree with Professor Milne, if he is the reviewer quoted in *Nature*, that the present explanation fails. The facts which he assumes are not proved, and even if they were, the interpretation should be exactly the reverse of that which he has given in *Nature*. Consequently we may dismiss this whole criticism as not well taken. Nothing is more certain than that movements of large masses within the earth adequate to displace the polar motion do not take place. A supposed effect of this kind is contradicted by all that we know of the rigidity and solidity of the earth under pressure of its own mass, which would prevent deep movements, and by the well-established fact that all earthquakes are shallow and the shock limited to one locality. Movements in the sea and in the atmosphere, however, might conspire to displace the pole and vary its rate of movement about the mean position, and the stresses thereby exerted upon the globe might occasion seismic outbreaks where the steam pressure had already approached the limits of stability. If the facts assumed by Professor Milne, are confirmed by time and experience, it is in this way that they must be explained; the outbreak of earthquakes being *occasioned*, but not *caused*, by the surface movements of water and air which displace the pole from its mean position and vary its rate of movement in different parts of the path, and thereby also the stresses exerted upon the different parts of the already unstable revolving globe.

§ 16. *On an Explanation of the Squeezing up of the Continents by the Settlement of the Ocean Basins given in Some Works on*

Geology.—In the work on "Geology" by Chamberlin and Salisbury, Vol. II., p. 129, we find the following curious figure and explanation of the elevation of the continents :

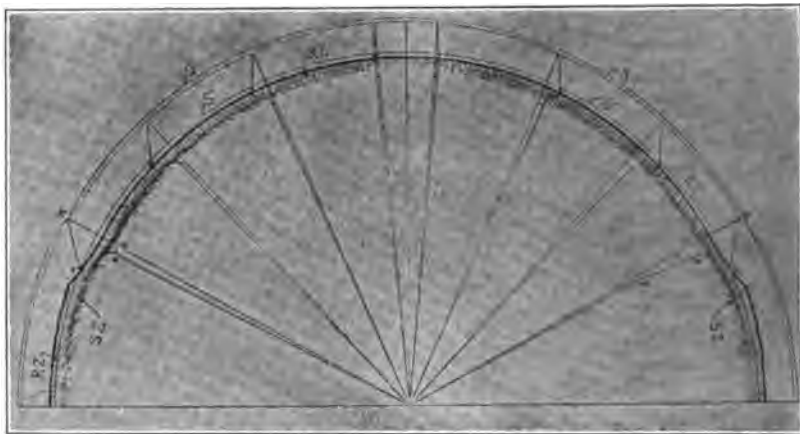


FIG. 3. Illustration of general deformative movement, from Chamberlin and Salisbury's "Geology," Vol. II., p. 129.

"FIG. 32 C. Diagram illustrating the supposed elements of a general deformative movement. *SS* represents the outline of the sphere at the ocean level before deformation. The dotted line represents the corresponding surface of the lithosphere, the ocean basin occupying the center and the continents the flanks. *S'S'* represents the outline of the sphere at the ocean level after deformation, the heavy line representing the outer surface of the deformed lithosphere, and the space between *SS* and *S'S'* representing (much exaggerated relatively) the vertical shrinkage which is the great feature of the movement but is only made apparent through its deforming effects. That part of the outer shell which is beneath the ocean is supposed to descend without much compression, while the necessary folding is concentrated on the borders of the continent. The central portion beneath the ocean is represented as descending directly toward the center. The portions on each side preserve their length by thrusting laterally and hence descend along paths represented by the arrow-headed lines, of which those at the border of the ocean, *a*, *a'*, are the most oblique and represent the greatest thrust. On the borders of the continent the crust is folded to the extent of this lateral thrust. This of course only holds true when the thrust is limited to a single oceanic basin. The lateral thrust is chiefly felt in the outer shell or rigid zone, *RZ*, which embraces the heavy line and the dotted zone below. Beneath this lies the shear zone, *SZ*, whose foliated structure is represented as not unlike that of the 'drag' belt of a fault plane. The igneous sheets, batholiths, etc., which are supposed to especially affect this zone are not represented. The great

sector beneath the ocean is represented as having crowded slightly upon the sectors beneath the continents on either hand, this crowding being represented by the short arrows b , b' . By comparing bb' with aa' the reason for the shear zone will be made apparent. On the right-hand side the outer part of the sub-oceanic sector is represented as crowding upon the continental sector an exceptional amount, as represented by the deflection of the line $b'b''$. This gives rise to the plateau at the right. The proportions of most of the significant parts are necessarily exaggerated relatively."

Let us now analyse this explanation a little more closely. These authors remark that "that part of the outer shell which is beneath the ocean is supposed to descend without much compression, while the necessary folding is concentrated on the borders of the continent." Is not this a purely gratuitous assumption, simply begging the question, and wholly unjustifiable? Why should the oceans descend without compression, while the continents are squeezed up at their edges? Obviously one has as much right to assume that the oceans are compressed by the sinking of the continents, as that the continents are compressed by the sinking of the oceans. Again, they say that "the portions on each side preserve their length by thrusting laterally and hence descend along paths represented by the arrow-headed lines, etc." But does not the assumption that "the portions preserve their length" imply that the ocean segment has not shrunk at all in respect to surface area, while the continent has been squeezed up at the edge to let it go down?

What right have we to assume a similar shrinkage in the radius of these sectors, and admit a shrinkage in one surface area (the continental) but deny it in another (the oceanic), which is much the larger of the two?

Could one imagine a more improbable effect of secular cooling?

Moreover the above figure corresponds to a shrinkage of about one tenth of the radius, or 400 miles. In view of the fact which has been shown in the paper on the "Temperature of the Earth" that our globe is not shrinking at all, it is unnecessary to make further comment on this unauthorized procedure.

But we may remark that in this "Geology," Vol. II., p. 131, we find a direct contradiction of the above explanation. It runs as follows:

"The continents now rise about 3 miles above the average ocean bottom, and much more than that in certain portions. Since the volume of the ocean has probably not greatly changed during known geological time and since the continents appear to have risen above surface, about as now, in the earliest known geological ages, it is assumed that similar differences of relief have prevailed at the various known deformative periods. We have seen that the gravitative pressure at 3 miles' depth is nearly or quite as great as the shearing-resistance at that depth. If a shearing-zone at depths of 3 to 5 miles had already been developed during the primary deformation, this would facilitate a reversed movement along the same shear-planes. It is therefore conceived that the continental platforms, by pressing upon their bases to the extent of 16,000 to 30,000 pounds to the square inch, would, though opposed by perhaps 5,000 pounds per square inch pressure from the oceans, gradually creep laterally under their own gravity, in a slow glacier-like way. This supposed lateral creep should be attended by crevassing, fissuring, and normal faulting; in other words, *by the prevalent tensional phenomena which the continents present*. It should be much more marked in the plateau regions than elsewhere, because of their superior elevation, and it is there that normal faulting is most pronounced."

Thus in one place we are assured that the continents have been squeezed up, in another that they are creeping down in a slow glacier-like way. If they are creeping down how were the mountains elevated? And why should these uplifts appear at the borders of the continents? Perhaps it will be answered that these two movements are going on together. But does not the first principle of the new theory tell us that neither of these supposed movements has any reality, and that the mountains and plateaus are elevated by the expulsion of lava from beneath the sea, the shells of which are thus carried to the greatest height in the gradual uplift of the land?

§ 17. *On the Folding and Distortion of the Strata seen at the Earth's Surface.*—In many works on geology the crumpling and folding of the strata are attributed to "a gentle warping of the soil." No doubt where mere settlement of the ground is in progress, owing to undermining, there is some warping of the soil; but this implies that the strata have already been uplifted and undermined, so as to become unstable. Such uplifting is the work of earthquakes, during past geological ages, though the settlement and warping may be due to the gradual undermining effects of water or other agency which produces instability. All movements of this kind are of small importance compared to the greater and more violent

derangements due to earthquakes. Many of the dislocations of the strata now seen on land originated when they were beneath the sea, and it would be a mistake to attribute any considerable part of these movements to seasonal or meteorological influences. It may be that the shape of the two sides of a valley undergoes an infinitesimal deformation from these causes, yet no important effects depend on such small deformations. They are all very superficial in character, whereas the causes which have folded the rocks of the earth's crust have been much more deep seated, and originate principally in earthquakes. When we see folded strata laid bare by erosion therefore we may assign the greater part of such effects to the "gentle warping of the soil" experienced in the dreadful shakings and derangements due to earthquakes of the world-shaking class. In observed plications of the strata earthquakes have supplied the principal part of the disturbing force. The important uplifts have all arisen in this way, and the instability thus resulting has produced the smaller displacements noted where the earth is settling.

The ground is more or less flexible near the surface, and sensible sagging may be produced by loading, but such effects are shallow and small in amount, and it would be a mistake to attribute to this cause important deformations of the strata. Is not such phraseology as the "gentle warping of the soil" therefore very unfortunate and misleading, and should it not be entirely given up?

§ 18. *Radium and other Atomic Sources of Energy.*—In the paper on the "Temperature of the Earth" we adhered to the gravitational theory as the only one which could be subjected to strict calculation. It is of course possible that there may exist in our planet unknown sources of atomic or subatomic energy such as are shown in radium and the related elements, which exhibit similar radio-active properties. At present, however, the amount of these elements known to exist in the earth is excessively small, and although this might account for the earth's internal heat; yet as gravitation is known to be a real cause and has been found sufficient to explain the observed phenomena, it is natural that a known source of energy which can be subjected to strict calculation should be preferred to one which is so wholly unknown.

Thus while we confined our estimates and calculations to gravitational energy, we do not deny the possibility that other sources of energy of an atomic or radioactive character may exist. If such sources really exist, the effect would be to prolong the period of the earth's history since consolidation.

At the present it is impossible to estimate these effects with any approach to accuracy, and we have therefore preferred to await the results of future research.

Our knowledge of radium and the rôle it plays in cosmical development is still much too limited to permit even a rough estimate of the effects of such subatomic energy. But it seems certain that radium has no sensible connection with volcanic eruptions, since in the rocks underlying the great extent of the continents it remains quiescent, and gives rise to no kind of outbreaks, though it may raise slightly the temperature of certain mineral springs. Remarkable as radium is, and wonderful as are its chemical actions, we are still unable to say that it plays any sensible part in cosmical processes outside of chemical transformations which lie in the domain of Mineralogy. The energy liberated in these transformations might, however, greatly prolong the past history of the earth, and the total duration might thus be extended from 10 to 100 million years.

III. ON THE DISTURBANCES OF THE EARTH'S MAGNETISM BY EARTHQUAKE AND VOLCANIC PHENOMENA.

§ 19. *Observations Show That Earthquakes and Volcanic Outbreaks Often Disturb Terrestrial Magnetism.*—It has long been noticed that volcanic outbreaks and also earthquakes are not infrequently accompanied by temporary disturbances of the earth's magnetic field. The cause of this is not yet understood and any conjecture at this time may be premature, nevertheless we are inclined to call attention to certain features of these phenomena which should be borne in mind.

1. As the earth's crust is thin, and the interior at an immense temperature, it seems highly probable, if not certain, that the magnetism of the globe depends upon the crust and the atmosphere, together with the sun's variable magnetic field in which our planet

revolves. That the incandescent nucleus could effect the magnetism of the earth seems highly improbable.

2. The annual and diurnal variations of the magnetic needle are most easily explained by the seasonal and diurnal effects of the sun, exerted indirectly through the paramagnetic medium of the atmosphere, the electric forces of which are modified by the sun's varying radiation of charged particles.

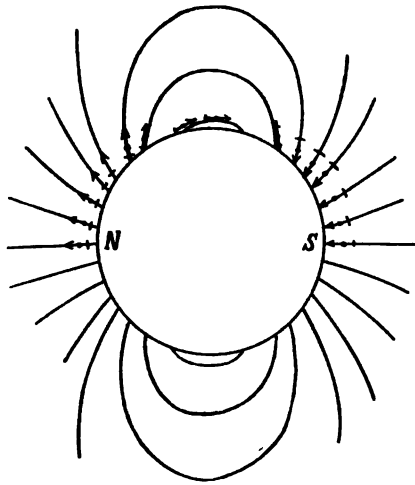


FIG. 4. Showing the lines of force about a spherical magnet, or a magnetized spherical shell, such as the crust of the Earth.

3. The aurora is one of these effects and has been treated by Arrhenius with characteristic penetration.

§ 20. *Gauss' Analysis of the Earth's Magnetism and the Conclusions Which May be Drawn From it.*—If we denote by $d\mu$ the quantity of magnetism present in an element of space, and by ρ its distance from any point in space, whose rectangular coördinates referred to any system may be x, y, z ; then we have for the potential function of the earth's magnetism

$$V = \int \frac{d\mu}{\rho}, \quad (1)$$

where the integration is to be extended over the entire volume of the earth. The forces resolved parallel to the coördinate axes are

$$-\frac{\partial V}{\partial x} = \xi, \quad -\frac{\partial V}{\partial y} = \eta, \quad -\frac{\partial V}{\partial z} = \zeta, \quad (2)$$

and the resulting force is given by the diagonal of the parallelepipedon

$$f = \sqrt{\xi^2 + \eta^2 + \zeta^2}. \quad (3)$$

If the direction and intensity of the force is found by observation all the desired elements may be calculated.

Passing to polar coördinates Gauss denotes by r the distance of the point from the center of the earth, and by u the angle which r makes with the north polar axis, and by λ the angle with the meridian made by a plane passing through the point and this polar axis. Symbols with subscripts zero refer to points in the earth.

Hence the expression for the distance ρ from any point in space is

$$\rho^2 = r^2 - 2rr_0[\cos u \cos u_0 + \sin u \sin u_0 \cos(\lambda - \lambda_0)] + r_0^2. \quad (4)$$

Accordingly the expression for the potential becomes

$$V = \int \frac{d\mu}{\sqrt{r^2 - 2rr_0[\cos u \cos u_0 + \sin u \sin u_0 \cos(\lambda - \lambda_0)] + r_0^2}}. \quad (5)$$

Considering the earth to be a sphere of radius a Gauss puts

$$-V = \frac{a^2}{r} P^0 + \frac{a^3}{r^2} P^1 + \frac{a^4}{r^3} P'' + \frac{a^5}{r^4} P''' + \dots, \quad (6)$$

the coefficients, P^0 , P^1 , P'' , etc., are functions of λ and u only.

If we develop the denominator under the integral sign in (5) in a series, the first two members of the series become

$$\frac{1}{r} + \frac{r_0}{r^2} [\cos u \cos u_0 + \sin u \sin u_0 \cos(\lambda - \lambda_0)] + \frac{r_0^2}{r^3} + \dots, \quad (7)$$

whence

$$a^2 P^0 = - \int d\mu, \quad a^3 P^1 = - \{ \alpha \cos u + \beta \cos \lambda + \gamma \sin u \sin \lambda \},$$

where

$$\alpha = \int r_0 d\mu \cos u_0, \quad \beta = \int r_0 d\mu \sin u_0 \cos \lambda_0, \quad \gamma = \int r_0 d\mu \sin u \sin \lambda. \quad (8)$$

As Gauss took the northern and southern magnetism to be equal and of opposite sign, it follows that

$$\int d\mu = 0,$$

and $P^0 = 0$. Hence we may put for points at the earth's surface, where $r = a$, and $P^0 = 0$.

$$-V = a(P' + P'' + P''' + \dots), \quad (9)$$

where P' , P'' , P''' , depend only on u and λ .

The magnetic potential for the earth calculated in this way represents observations with the desired accuracy. Since Gauss showed that any distribution of magnetism within the earth, as respects the effects in outer space, may be completely represented by an appropriate surface distribution, it follows that the existing distribution of the earth's magnetism is most probably confined to the crust of the globe. In fact this is the only part of our planet sufficiently cooled to maintain magnetic properties once established in its elements. The field of force thus arising about the earth might, however, be slightly modified by electric and other effects depending on the sun and moon, and the diurnal movement of the illuminated hemispheres of our globe. These effects as determined by observation are much too large to be ascribed to direct actions of the sun and moon, and are believed to be indirect effects depending largely on charges operating in the upper regions of our atmosphere.

This upper atmosphere is always exposed to the radiation of the heavenly bodies, and no doubt accumulates a potential powerful enough to influence the field near the earth's surface. Discharge of this potential is witnessed in the aurora borealis, which is accompanied by conspicuous disturbances of the earth's magnetism. Gauss showed that the location of the constant part of the earth's magnetism must necessarily be in the body of the globe, and not in the atmosphere or outer space.

In his "Algemeine Theorie des Erdmagnetismus," 1838, Gauss treated of a sphere magnetised in any manner. If X , Y , Z , be the components of the earth's resultant magnetic force at any point on the surface, in the directions of geographical north, west and the zenith of observer, the horizontal intensity H , declination δ , and inclination ι , are fully defined by the equations:

$$H = \sqrt{X^2 + Y^2}, \quad \tan \delta = \frac{Y}{X}, \quad \tan \iota = \frac{Z}{\sqrt{X^2 + Y^2}}. \quad (10)$$

If V be the magnetic potential of the earth, l the latitude, and λ the longitude of any point on its surface, and if a be the radius of the earth assumed to be spherical, we shall have

$$X = -\frac{1}{a} \frac{\partial V}{\partial l}, \quad Y = -\frac{1}{a \cos l} \frac{\partial V}{\partial \lambda}, \quad Z = -\frac{\partial V}{\partial r}, \quad (11)$$

where r is the distance of any point from the center of the earth.

If $S_1 + S_2 + S_3 + \dots S_i$ be a convergent series of spherical surface harmonics defining for every point of its surface the potential of all the magnetized molten or electric currents within the earth, the potential at all external points will be given by the series

$$V = S_1 \left(\frac{a}{r}\right)^2 + S_2 \left(\frac{a}{r}\right)^3 + \dots + S_i \left(\frac{a}{r}\right)^{i+1}, \quad (12)$$

The functions $S_1, S_2, S_3, \dots$ are functions of known form, containing $3, 5, \dots 2i + 1$ constants; and if we neglect terms beyond the i th order, there will remain in the expression for V $i^2 + 2i$ arbitrary constants. These constants may be determined by observation, and then the magnetic action at all points on the surface or outside the earth becomes known irrespective of the internal distribution of the magnetic causes which are inaccessible to observation.

§ 21. *The Mutual Potential Energy and Mutual Action of Two Magnetic Systems.*—If any portion of the earth's crust or an atmospheric current above it should be suddenly magnetized by an instantaneous charge of electricity or otherwise, during the violent commotion of an earthquake or volcanic outburst, we should have at least a temporary magnet suddenly formed in the field of the earth's magnetism, and the result would be the disturbance of the magnetic needle. Whether the magnetism of the earth be distributed according to Poisson's theory, with a certain volume distribution of density ν and a surface distribution of density σ ; or according to Gauss' theory, with a distribution wholly on the surface, this result is equally true.

To determine the mutual action of two magnets on each other requires the evaluation of a sextuple integral, every point in one field of space acting upon the corresponding points of the other. If W be the potential energy of the whole magnetic system, R and R'

the resultant forces at any point of space due to the acting and acted-upon systems respectively, θ the angle between their directions, and dv the element of volume occupied by any element of magnetism, we have (Encyclopedia Britannica, article "Magnetism," p. 230):

$$W = + \frac{1}{4\pi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} RR' \cos \theta dv. \quad (13)$$

Now unless R or R' is zero, so that the elements of the triple integral vanish, or one of the magnets exerts only an infinitesimal force upon the other, this mutual potential energy is always finite. Accordingly, whenever a new magnet of sensible power is suddenly developed in the field of the earth's magnetism, the magnetic needle necessarily is disturbed, as in earthquakes and volcanic outbursts. The fact that such disturbances are so repeatedly observed, leaves no doubt of the development of temporary magnets in the earth's field of force; and the intensity of the disturbance necessarily is greatest near the place where the second magnet is developed. Hence the disturbance of the needle by such outbreaks indicates the generation of temporary magnets in the earth's crust, and especially in the atmosphere. The dissipation of the charge restores quiescence to the earth's magnetic field, and the needle ceases to tremble.

§ 22. *Terrestrial Magnetism Modified by Irregularities in the Earth's Crust.*—In the *National Geographic Magazine* for September, 1907, Dr. L. A. Bauer has a review of the work done by the *Galilee* in the survey of the North Pacific ocean authorized by the Carnegie Institution. After describing the work already done he adds:

"An all-sailing vessel, however, does not permit the magnetic survey to be undertaken with the completeness and success demanded, since with such a vessel it is more or less dangerous to investigate the magnetic irregularities almost invariably shown to exist near land masses. The mapping of these irregularities is of the greatest importance to the mariner, as in many cases they are sufficient, if not allowed for, to land a vessel on the rocks."

The land masses accessible to the navigator are either islands or shores, and thus irregularities of surface like the mountains which we see on land; and the change in the magnetism near mountains is also well known. It follows therefore that irregularities of sur-

face sensibly affect the magnetic needle in the neighboring region. This conspicuous effect would not be likely to arise if the magnetism depended on the whole earth, rather than on the crust, and hence it seems to indicate that the seat of the earth's magnetism is essentially shallow. Not only may we attribute the permanent magnetism to the crust, but we may also affirm that the upheavals of the crust which have produced mountains have given rise to variations of the local field.

Just how this arises may not be affirmed with entire certainty; but the fact that disturbances have been noted during earthquakes would seem to indicate bodily movement of magnetic matter, or ordinary matter temporarily rendered magnetic.

The outburst at Mt. Pelée, May 8, 1902, which instantly disturbed the magnetic needle over a wide area, was probably due to the ejection of a great mass of burning vapor high into the air, which thus gave rise to such electric energy that the earth's magnetic field was suddenly disturbed.

The eruption at Krakatoa produced a very similar effect, the sudden development of an atmospheric charge vastly exceeding that due to the greatest hurricane. (Report of the Krakatoa Committee, Royal Society, 1887.) A hurricane develops gradually and the effect is scattered over a wide area; a volcanic outburst is sudden and so concentrated that a considerable disturbance of the earth's magnetic field may easily result. It is somewhat analogous to the aurora borealis, but the location and cause is different and the effect may be less rapid. In the aurora there is a discharge between the upper and lower regions of the atmosphere, and this redistribution of the magnetic tension in the earth's atmospheric system causes a fluctuation of the magnetic needle, or a so-called magnetic storm.

Now in the case of a violent volcanic outbreak there is a similar disturbance, owing to the sudden injection of a highly electrified charge into the lower parts of the atmosphere, and the exchange with the upper region continues for some time. Also when great earthquakes occur there is violent shaking of a considerable region of the earth's crust, and consequently some temporary, and perhaps permanent, derangement of the elements of magnetism, owing

to the agitation and to the movement of streams beneath the crust. These seem to be the most probable causes of the changes in the earth's magnetic field, often noticed to disturb the needle at the time of earthquakes and volcanic eruptions; but our knowledge of the subject is still in its infancy and we must be cautious in drawing conclusions. Some of the disturbances of course are purely mechanical.

The comparatively slow propagation (868 miles per hour) of the magnetic disturbance at the time of the Krakatoa outbreak, August 27, 1883, might be ascribed to the undulatory commotion in the upper air, since sound so propagated would have about this velocity. It would seem to depend more upon the indirect effects of a disturbance of the air than upon the forces exerted by a direct magnetic charge. Both causes are no doubt at work in certain disturbances, and time must decide just how the effects are propagated.

CONCLUSION.

At the close of the two former papers on the physics of the earth, the chief results at which we arrived are briefly summarized. In the same way we may here add a recapitulation of the results which are more fully established in this third paper.

1. It has long been customary to refer mountain making to catastrophes in remote geological ages, and to suppose that the formation of mountains is not going on upon the earth at the present time. Such supposed spasmodic activity is contrary to the whole order of nature and to the doctrine of evolution by which we labor to interpret animate and inanimate phenomena. On the other hand the discovery of mountains in the depths of the sea has excited the surprise without satisfying the wonder of the naturalist, so that the whole subject has become involved in darkness.

2. The doctrine of continuity, as respects both time and space, permits us to view earthquakes, mountain formation, and kindred phenomena, merely as a part of an unbroken whole which has come about by the steady action of natural laws operating not only along the borders of the continents, but also in the depths of the ocean. A theory which unites and harmonizes these phenomena,

and thus explains the mountains on land, as well as those in the depths of the sea, by a common cause, operating not only throughout past geological ages, but also at the present time, will naturally have a strong claim to acceptance.

3. We have therefore labored to establish some undeniable cases of mountain formation now going on in the depths of the sea, and have shown by the theory of probability, based merely on contiguity of positions and similarity of volume between the deep trench off the Aleutian Islands and the ridge which runs parallel to it, with peaks here and there projecting above the water as islands, that the chances are at least a decillion decillions to one that the ridge and adjacent depression are physically connected and have had a common origin. As an island of the ridge is frequently uplifted by an earthquake, while the bottom of the trench sinks, as shown by the withdrawal of the water before the inrush of the accompanying seismic sea wave; and as this corresponds to an expulsion of lava from beneath the trench towards the land, or away from the body of the Pacific ocean, and the volume of the ridge corresponds to that of the trench, the probability that one developed from the other is converted into an absolute certainty.

4. The expulsion of lava from the ocean towards the land and the breaking out of numerous islands into volcanoes, emitting chiefly vapor of steam, shows that the subterranean movement can depend on nothing whatever but the secular leakage of the ocean bottom, which is most rapid where the sea is deepest, in accordance with the observed recurrence of earthquake phenomena.

5. Undeniable cases of mountain formation now going on in the depths of the sea may thus be located in various parts of the world. We have cited such cases in the Aleutian, Kurile, and Japanese islands; in the East Indies, between New Zealand and Samoa, and along the coasts of various continents. Many more may be found by the further study of the sea bottom and of the earthquakes now disturbing it.

6. It thus seems undeniable that earthquakes in the sea and along the sea coasts have the highest geological significance. In fact no other forces are at work crumpling the earth's crust, as seen in mountain ranges, islands, and plateaus; and the absence

of mountain forming movements in the interior of the continents shows that all these effects depend upon the sea, or upon surface water generally, and not at all upon the progress of the secular cooling of the globe.

7. Researches into the physics of the earth based on the hypothesis of gravitational instability may be interesting mathematically, but a study of the earth's surface shows that all the important crustal movements now going on result from the influence of the sea; and hence the conclusions deduced from the theory of gravitational instability are invalid, because, ingenious and correct as they are on the hypothesis, they rest on a false premise.

8. In the same way it is shown that no sensible shrinkage results from secular cooling; on the contrary the globe seems to be undergoing a gradual secular expansion, owing to the influence of the sea in uplifting mountains, plateaus and other masses of land, by the injection of lava saturated with steam, which forms underlying masses of pumice of various degrees of density. The expansion of the globe seems to be at least ten times more rapid than the contraction due to secular cooling; and the great distance to which the sea has withdrawn from some of the mountain ranges, and the great height to which the plateaus have been uplifted, exhibits the mighty effects of this cause in the course of geological ages.

9. The seat of terrestrial magnetism seems to be the earth's crust and the surrounding atmosphere; irregularities in the magnetic forces arise from the sun and moon, while similar disturbances accompany earthquakes and volcanic outbreaks, which suddenly agitate the air and change the electric condition of matter in the field of the earth's magnetism. The irregularities near islands and land masses noticed in ocean surveys indicate that the permanent magnetism is confined chiefly to the solid crust, and does not depend on the great incandescent nucleus of the globe. Magnetic storms and aurorae depend on atmospheric charges derived principally from the sun and moon.

10. It is thus proved not only that earthquakes, volcanoes, mountain formation, the formation of islands and plateaus, seismic sea waves, and the feeble attraction of mountains long noticed in

geodesy, are closely connected and mutually dependent upon a single physical cause, namely the secular leakage of the ocean bottoms; but also that the magnetism of the earth is intimately connected with the forces which modify the earth's crust, because the chief seat of the permanent magnetism is shallow. Thus seven great classes of natural phenomena are shown to be mutually connected and dependent on the forces which have crumpled the crust of our planet.

11. In the paper on the temperature of the earth it was shown from the mathematical theory of heat as applied to the secular cooling of the globe that when the gravitational potential of the mass alone is the source of energy considered, the most probable age of the consolidated earth is some ten million years. Variations of the data there used might possibly double this age, but it is doubtful if further extension of the time limit of the past history of our planet is possible without invoking the aid of subatomic energies as exemplified in radium and kindred radio-active substances. At present we know too little of radium and similar elements to be able to affirm with confidence that the heat resulting from the transformation of these substances does not prolong the life of our planet; yet as radium has no known connection with volcanoes, earthquakes, and mountain formation, but, from the absence of outbreaks in the interior of continents, seems to be everywhere in an essentially quiescent or dormant condition, it is natural to infer that it plays only a subordinate part in cosmical processes. It may, however, be of great importance in chemical transformations, which belong to the domain of Mineralogy, and relate to the crust, rather than to the body, of our globe. Without, therefore, wholly denying the cosmical importance of radium, we calmly await developments which will show its correct place in the order of nature. As the energy derived from radium would counteract the effects of secular cooling it may have greatly prolonged the history of the encrusted earth.

12. In the investigation of phenomena so complex as those connected with the physics of the earth, we must not expect the real underlying physical cause to be entirely clear in every case, because the present state of the globe presents to our contemplation natural

processes in every stage of development, and the aspect obviously will be different in different stages. If we can find the true laws exemplified in a few typical cases in which the meaning of the phenomena is free from doubt, we may legitimately hold that in all cases the phenomena were more or less similar at one stage of their existence. Considering the vast age of the earth and the insignificant period of human history, and the much briefer time covered by intelligent observations, we seem indeed fortunate to be able to recognize the true processes in even a few typical cases of crustal transformation. For the life of the individual is as nothing in the history of our planet. Accordingly the simplest natural laws, which lie at the basis of the physics of the earth, we have discovered and confirmed beyond all doubt; and we may safely leave to the future the extension and verification of the theory of the secular leakage of the ocean bottoms, of which we have been able to lay only the general foundation.

But even a mere outline of the processes which lie at the basis of the physics of the earth is likely to clarify and simplify our views of the order of nature. The complete development of that beautiful science will be a work of the future, and for the present we must rest content with the recognition of true physical causes, without which order and harmony and proper relationship between different classes of phenomena could not be established, however great the number of observations. The chief danger in science to-day is that in the midst of such vast multitudes of special observations as are being accumulated, the few true causes, which give order and harmony to the whole body of phenomena, will be lost sight of. Without these underlying principles for guiding our thought, according to nature's laws, the mere accumulation of disconnected facts may become a burden to oppress, rather than a starry ray to illuminate, the human mind. Principles are therefore vastly more important than observations, though accurate observations always are required in their deduction; because where the underlying laws are confirmed they give the solid foundations for a real science, which enable us to understand the observations of all time.

BLUE RIDGE ON LOUITRE,

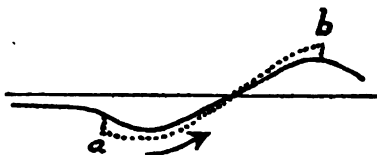
MONTGOMERY CITY, MISSOURI, October 24, 1907.

ADDENDUM.

§ 23. *On the Sinking of Deep Trenches in the Sea Bottom.*—

Since the above paper was finished it has occurred to the writer to point out a little more clearly the circumstances which may lead to the sinking of the sea bottom, when lava is expelled from beneath it. In the accompanying figure, the process of mountain formation is supposed to be going on. The expulsions of lava naturally are accompanied by a sudden relief of crustal stress, and a mighty horizontal thrust in the direction of the movement, as the lava is pushed under the land.

This terrific lateral pressure is powerful enough to push the lava along under the crust, in spite of the great weight of the latter. By this enforced movement the ridge is elevated, as at *b*, and at the



same time the crustal block moved a good many feet in the direction of the land; this stretches the sagging crust, and pulls it apart along certain fault lines under the sea, as at *a*; so that when some of the support from beneath is withdrawn by the expulsion of part of the supporting lava, and the fault opened, by the horizontal movement, the crust naturally gives down. The shaking accompanying the horizontal thrust of the crust opens the fault under the sea, thus temporarily removing the friction of one crustal block against another and permitting the walls to slide without great resistance. And as the support is weakened by the simultaneous expulsion of part of the underlying lava, sinking necessarily follows.

From these considerations we see that sinking is most easily brought about where the ridge is sharply elevated so as to permit some lateral movement. It is true that the inclination of the crustal block throws a little more weight on the side under the sea and this would increase the resistance; yet when the fault is opened during the vibrations of an earthquake sinking the more easily takes place. This explanation enables us to understand why sinking of the sea

bottom, as shown by the accompanying seismic sea wave, so frequently occurs during great earthquakes.

The force of the argument that the ridge was uplifted by matter actually expelled from under the trench is easily seen from a familiar illustration often met with in a smooth field or on the plains. If we go along over the level ground, and all of a sudden come upon a mound with a sink hole near it of about the same volume, we immediately conclude that the mound builders or pond diggers have been at work. It is obvious that the mound is made of soil which came out of the hole. In the same way, if we came upon a ditch with a ridge to one side, of such volume that it would about fill up the former, we know with even greater certainty that ditch diggers have taken the soil out of the trench and piled it upon the bank.

Now the trenches in the sea bottom, with parallel ridges of nearly equal volume, have all the force of this familiar argument; but as they have not been dug from above, it follows that the matter is transferred beneath the crust, by subterranean bodily movement of the kind we have described; and hence the crust has been crumpled correspondingly, the ridge running parallel to the trench from which the matter was expelled.

§ 24. *On Darwin's Theory of Coral Islands.*—This investigation throws decided light upon Charles Darwin's famous theory of the sinking of the ocean bottom, as inferred from the study of the coral reefs. It shows that while sinking often takes place, elevation also is very common. The chief difference is that elevation kills the coral, and the islands gradually become covered with vegetation, while only those in which sinking predominates become surrounded by coral reefs. It is well known that there are many islands in the sea with coral rock above the water; a good illustration is afforded by the eastern end of Guam, where a huge block has been uplifted, as shown by the vertical walls. Islands which have been recently uplifted often are volcanic, so that coral appears especially about old islands, many of which are subsiding, owing to a change in the direction of movement beneath the crust. Forces which formerly produced elevation are now changed in direction and working so as to produce a slow subsidence. Charles Darwin's theory of coral reefs is therefore confirmed, but it does not explain all the phe-

nomena noticed about the islands in the sea. It happens also that some islands once built around by coral are again upraised by a recurrence of the elevating movement; yet this probably would not be the usual phenomenon, so that in general Darwin's observations on coral reefs accord with the theory, and are what one might naturally expect to find on an ocean-covered planet with leaky and oscillating crust.

§ 25. *On the Modification of Secular Cooling by Radium.*—In regard to the age of the earth, it ought to be remarked that if radium be taken into account, the heat resulting from its secular disintegration would prevent the crust from thickening, except very slowly; and consequently with so thin a crust as that of our actual globe the period of time since the consolidation, as calculated in the paper on the "Temperature of the Earth," is too small. Accordingly although we found the period to be of the order of ten million years, yet if radium be introduced the duration of time might be lengthened to one hundred million years, or even to a greater period. And if this energy due to radium be admitted for the earth, it could not well be denied for the sun, so that the period of the sun's activity would be lengthened correspondingly. Hence the more moderate of the immense periods of time demanded by geological phenomena may be conceded. Time must decide to what extent these demands are justifiable. At present we may await future developments with entire confidence that the causes now known are sufficient to explain all terrestrial phenomena.

§ 26. *Favorable Reception of the Present Theory by Physicists and Geologists.*—The lively interest awakened by the two preceding papers among physicists and geologists and other men of science, as shown by letters which have reached the writer, indicates a much more favorable reception of the present theory than might have been anticipated. Indeed its general acceptance seems fully assured, and many questions are thus raised of great importance in natural philosophy. All who have considered the question attentively seem to agree that it is very improbable that the ocean bottom is watertight. One of the most eminent of living physicists expresses the opinion that this cannot be true, unless the nature of the rock is greatly modified by pressure. Such modification under pressure he

thinks cannot take place in the first twenty miles of the earth's crust, because the pressure is not great enough to prevent secular leakage under the constant pressure of the oceans, which in many places is sufficiently powerful to throw a column of water five miles high.

No doubt this view will be generally adopted by physicists and geologists. One may indeed see that it is true by remembering that at a depth of twenty miles the pressure is only about 8,600 atmospheres, or a little over eight times what it is in the deepest oceans. Such pressure might indeed tighten the crystalline elements of granite, but it could not obliterate the crystals; and hence capillary forces would be intensified rather than diminished by this tightening up of such a coarse-grained structure.

We cannot experiment on rock subjected to such pressure as exists at a depth of twenty miles, but we can observe lava expelled from volcanoes, some of which was once compressed at this depth; and we can examine the granite at the base of vertical walls where faults have moved under earthquake forces for many thousands of feet. In neither case does the structure of the rock indicate that great modification would occur at so small a depth as twenty miles.

But the most conclusive answer which nature gives to this inquiry is furnished by the vast vertical walls of granite so often lifted thousands of feet by fault movements in such places as the Andes of Peru, Chile and Patagonia, where the leakage of the ocean has found relief by the expulsion of lava under the land along the margins of the sea. The meaning of the mountain formation along such a sea coast admits of no possible doubt. Accordingly we are enabled to interpret the movements beneath the crust, and to infer the nature of the underlying rock, even where it is wholly inaccessible to observation.

BLUE RIDGE ON LOUTRE,
MONTGOMERY CITY, MISSOURI,
Jan. 14, 1908.

ERRATA.

(a) In the paper on the CAUSE OF EARTHQUAKES:

On page 311 the formula for n should read $n = \frac{4400}{66} = 66\frac{2}{3}$.

The account of the changes produced by the Valparaiso earthquake, p. 328, appear to be open to some doubt. Exact data are not yet at hand. This detail of course does not affect the argument in the paper.

(b) In the paper on the "Temperature of the Earth":

(1) On page 196 the formula should read $\frac{Q}{W} = \frac{k - \epsilon}{k - 1}$.

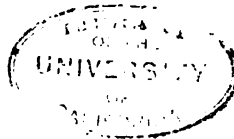
(2) Near bottom of page 196, and middle of page 197, *Auwendungen* should read *Anwendungen*.

(3) On page 216, $\frac{d\theta}{dx}$ is taken to be $\frac{1}{61}$; and the exponential factor is neglected, because it appears in the second power, and for a depth of twenty miles is equivalent to $e^{-\frac{1000}{(16)^{21}10^{20}}} = e^{-\frac{1}{266}}$ and thus nearly unity for $t = 100,000,000$ years; for $t = 10,000,000$ years, the result is $e^{-\frac{1}{2.56}} = \frac{1}{1.48}$, which would make t still smaller, in the ratio of nearly $2/3$ (0.676). There is therefore a slight defect in the solution for values of t so small as 10,000,000 years; but as it reduces the time to a still smaller interval, we need not further consider it. The values of t given in the paper on the "Temperature of the Earth" are therefore slightly too large for rigorous solutions of the equations.

3

**FURTHER RESEARCHES ON THE PHYSICS OF THE
EARTH, AND ESPECIALLY ON THE FOLDING OF
MOUNTAIN RANGES AND THE UPLIFT OF
PLATEAUS AND CONTINENTS PRODUCED
BY MOVEMENTS OF LAVA BENEATH
THE CRUST ARISING FROM THE
SECULAR LEAKAGE OF THE
OCEAN BOTTOMS.**

BY T. J. J. SEE, A.M., LT.M., SC.M. (MISSOU.), A.M., PH. D. (BEROL.).



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BY T. J. J. SEE, A.M., LT.M., SC.M. (MISSOU.), A.M., PH.D. (BEROL.),
PROFESSOR OF MATHEMATICS, U. S. NAVY, IN CHARGE OF THE
NAVAL OBSERVATORY, MARE ISLAND, CALIFORNIA.

(Read April 24, 1908.)

I. GENERAL CONSIDERATIONS ON THE PHYSICS OF THE EARTH, WITH
ESPECIAL REFERENCE TO THE SECULAR LEAKAGE OF THE
OCEANS AND THE RESULTING DEVELOPMENT OF
MOUNTAINS, PLATEAUS AND ISLANDS.

§ 1. *Introductory Remarks.*—In three papers recently communicated to the American Philosophical Society held at Philadelphia and since published in the proceedings of that Society,¹ the writer has treated at some length of the cause of earthquakes, moun-

¹ 1. "The Cause of Earthquakes, Mountain Formation and kindred phenomena connected with the Physics of the Earth," PROC. AM. PHILOS. SOC., 1906.

2. "On the Temperature, Secular Cooling and Contraction of the Earth, and on the Theory of Earthquakes held by the Ancients," PROC. AM. PHILOS. SOC., 1907.

3. "The New Theory of Earthquakes and Mountain Formation as illustrated by Processes now at work in the Depths of the Sea," PROC. AM. PHILOS. SOC., 1907; issued in March, 1908.

The following shorter articles have also appeared:

4. "Outline of the New Theory of Earthquakes," *Popular Astronomy*, April, 1908.

5. "How the Mountains were Made in the Depths of the Sea," *Pacific Monthly*, Sept., 1908.

Reprinted from Proceedings American Philosophical Society, Vol. xlvii. 1908.

tain formation and kindred phenomena connected with the physics of the earth. In the course of these three memoirs many important questions are considered, and it seems to be rendered highly probable that six great classes of phenomena, not heretofore closely associated, depend on a single physical cause, namely, the secular leakage of the ocean bottoms, and the resulting movement of molten rock beneath the earth's crust. The six classes of phenomena traced to a single physical cause are: (1) world-shaking earthquakes; (2) the activity of volcanoes; (3) mountain formation; (4) the formation of islands and plateaus; (5) seismic sea waves; (6) the feeble attraction of mountains and plateaus long noticed in geodesy.

The first of the memoirs printed by the American Philosophical Society deals with the problem of earthquakes in its general aspects, and sets forth grounds for the theory that these six classes of phenomena are directly connected and dependent on a single physical cause; the second examines the question of the earth's temperature, secular cooling and contraction, and endeavors to show that the traditional theory of the changes noticed on the earth's surface is not well founded; while the third seeks to demonstrate the more important conclusions reached in the first memoir, by an appeal to processes now at work in the depths of the sea, the meaning of which apparently is so plain as to admit of no possible doubt.

The change in the point of view necessitated by the considerations brought forth in these papers is so remarkable as to be worthy of the attention of all who are interested in the grand science of natural philosophy. And we therefore propose to consider in this paper the physical basis of the theory of ocean leakage, the folding of mountain ranges and the uplift of plateaus and continents produced by movements of lava beneath the crust, together with the historical aspects of the problems of the physics of the earth. Heretofore the nature of the forces which have folded mountain ranges and their relationship to those slow movements which have raised whole continents have been equally mysterious and bewildering to the investigator. Accordingly any light which may be shed on this difficult subject will no doubt be exceedingly welcome to those who are interested in the progress of the physical sciences.

As the leakage of the oceans seems to be clearly proved by the movements noticed in earthquakes, especially where mountain formation is now going on in the depths of the sea, and the seismic disturbances are therefore accompanied by the sinking of the sea bottom, as shown by the seismic sea waves which follow the earthquakes, it seems legitimate to appeal to these movements of molten matter beneath the earth's crust as the only available means of demonstrating the porosity and other physical properties of layers of granite twenty miles thick. Owing to the restricted conditions of human life, no experiments on such a grand scale can ever be attempted in our laboratories, however great the facilities at our command; and our only means of ascertaining the truth with regard to the theory of ocean leakage is by careful observation in the great laboratory of nature. The leakage of the oceans involves three important questions: (1) The porosity of thick layers of matter such as those composing the earth's crust; (2) the penetrability of the crust under steady fluid pressure, by which the capillary forces are made to aid the molecular forces producing penetration of the fluid; and (3) the accumulation of stresses depending on the formation of steam in the layers just beneath the earth's crust.

The conditions existing in nature can scarcely be approximated in our laboratories, on account of the limitations of the forces at our command, but so far as experiments throw light on these great questions, the evidence tends to confirm the theory of ocean leakage. The well-known experiments of Daubrée, showing that under the action of capillary forces hot water will penetrate a layer of sandstone against a strong counter pressure of steam, and by entering a cavity actually increase the steam pressure on the further side, has been justly held to afford evidence of the leakage of the earth's crust, and of the probable mode of volcanic activity. If such action is possible in a minute way, it may easily operate on a vastly greater scale to produce the shaking of the crust in earthquakes, together with the uplift of mountains and the occasional outbreak of volcanoes.

Now if the rock of the earth's crust is at all as porous as we generally think, the constant pressure of the vertical column of

water, often miles deep, resting on the ocean bed must tend to force the fluid deeper and deeper into the bowels of the earth. A study of what takes place on our earth under the observed conditions constitutes therefore one of the grandest problems in natural philosophy.

Indeed it may be said that the great laboratory of nature has magnificent experiments constantly going on. All that we need to do is to interpret these experiments correctly. The best way to do this is to select phenomena in which the processes are so clear as to be free from doubt; after we have found the law of the phenomena in cases which are beyond question, we may then generalize and interpret other phenomena, in which the relations are not so obvious. By gathering principles and laws from cases which are entirely clear, and working by degrees to understand those which are more obscure, we may finally arrive at the true processes even when the operations of nature are quite hidden from our view.

Laws thus established by observation in the great laboratory of nature will obviously hold true of like experiments in the minute physical laboratories designed by man; and by noting the phenomena of the globe we may extend our knowledge of the universal properties of matter under various physical conditions often more extreme than those ordinarily witnessed at the surface of the earth.

§ 2. *Heretofore the ocean bottoms have been assumed to be watertight.*—The earth's crust is made up chiefly of sedimentary, igneous and granitic rocks, and soil produced by the decomposition of the various kinds of rock under the action of water and the atmosphere. Nearly all of the sedimentary rocks are quite leaky, and moreover they absorb a great deal of moisture from the air; the formation of artesian wells and of natural springs depends primarily upon the percolation of water through rocks and layers of soil of various kinds. The leaky character of the sedimentary rocks is well known and has been generally recognized. But these rocks exist only near the surface, and do not extend more than a very few miles deep; consequently they could admit the water to but a slight depth into the earth's interior. Below the sedimentary rocks lies the mass of granite which makes up by far the greater part of the earth's crust. The granitic rocks, such as granite, andesite, dia-

base, etc., are by no means so penetrable as the sedimentary rocks, and hence water has more difficulty in passing through them. And as the layers of this material composing the earth's crust are about fifteen miles deep, it has been generally held that water would have difficulty in making its way down into the heated layers just beneath the crust.¹ Indeed it has been practically assumed that the ocean bottoms are water-tight, in spite of the great fluid pressure constantly exerted by the mere depths of the water over a large part of the bottom of the sea. This fluid pressure in many places is great enough to throw a column of water to the free surface, over five miles high; and it operates not only from day to day, year to year, but also from century to century, age to age. If granite is at all penetrable by water, is it therefore any wonder that a gradual secular leakage should go on, and at length, by a kind of slow perspiration of the stone, give rise to sufficient accumulation of steam beneath the crust to produce a swelling of the saturated mass, and require a readjustment of the overlying rocks?

Now it happens that by nature all the granitic rocks are crystalline, and thus somewhat coarse-grained in structure; so that they absorb water from the ground and moisture from the air. The crystalline structure permits penetrability to a greater degree than would fine-grained and very hard rocks such as agate; but no rock has such fine pores as the metals, and especially vitreous bodies like glass, to which agate is an approximation. And as all the metals are proved by experiment to be leaky under great fluid pressure, and glass is shown to obey the same law, it obviously follows that all rocks are leaky under great fluid pressure. Consequently under the incessant pressure of the oceans' water must make its way into the heated layer just beneath the earth's crust.

Heretofore the possibility of earthquakes cracking the ocean bottom has been generally recognized, but it has been held that

¹ This statement is perhaps too positive, for Sir William Ramsay, the celebrated British Chemist and Physicist, writes me that he has long believed that the ocean bottom leaks and that the formation of minerals takes place chiefly in the bed of the sea. Undoubtedly this view will come to be generally accepted. Similar views seem to be held by Lord Rayleigh, Sir Wm. Huggins, Arrhenius and many other eminent physicists.

crevices thus formed would not extend over five or six miles deep before they would be closed by the effects of pressure, which naturally increases rapidly as we descend into the earth. The belief has therefore prevailed that although the bed of the sea might be rent by an earthquake, it would immediately close up again, and water would thus be prevented from entering the bowels of the globe.

It scarcely seems to have occurred to investigators to consider the effects of the constant hydrostatic pressure resulting from the depth of the sea, in forcing the water slowly through the fifteen miles of granite composing the earth's crust. A crevice is small, and would let in but little water when closed up quickly; but the whole sea bottom is large, and unless it is really water-tight, even a slow leakage over a large area would at length develop stresses beneath which would necessitate a readjustment of the overlying blocks of the crust. This readjustment is ordinarily called an earthquake.

Moreover the great abundance of submarine earthquakes has been largely overlooked by previous investigators. It is the secular effect of the constant pressure of the oceans and of capillary forces in promoting the downward movement of the water which has been generally lost sight of.

But if we admit on the basis of experimental evidence that water can penetrate thin layers of granite, the question naturally arises: Can it also penetrate a layer of granite fifteen or twenty miles thick? It seems obvious that it can, because for small or moderate pressures water is nearly incompressible and would not sensibly increase in density as it went down into the globe. The fluid which passed through the upper layer of granite would therefore keep on descending, under the increasing fluid pressure from above, and at length the whole layer would be saturated, and perspiring below with a steady leakage which would give rise to tremendous steam power in the underlying molten rock. Thus great stresses due to slow accumulation of steam would develop in the layer just beneath the crust, and this would give rise to earthquakes and mountain formation.

Among the practical men of science to whom the problem of ocean leakage was submitted, we might name some of the most

eminent of living physicists. While disclaiming especial authority to pass upon such a question, they expressed the opinion that it was very improbable that the ocean bottom could be water-tight, unless the nature of the rock was greatly modified by pressure, which could hardly be the case in the first twenty miles of the earth's crust, where the pressure does not exceed 8,600 atmospheres.

Whatever doubt might attach to this solution of the problem, from an experimental standpoint, where positive knowledge is greatly lacking, seems to be dispelled by the phenomena noticed in the sea bottom in various places, which show that lava is expelled from beneath the sea and pushed under the adjacent land. The phenomena noticed in the laboratory of nature thus prove the leakage of the ocean from an observational standpoint, because they admit of no other interpretation.

§ 3. *The Theory of Water-tightness of the Ocean Bottoms Disproved by the Expulsion of Lava from under the Sea.*—Just south of the Aleutian Islands, a long, narrow and deep trench just parallel to this chain has been dug out by the expulsion of lava from beneath the sea. The nature of this trough is illustrated by the accompanying Map.

It will be seen that the island chain adjacent to the trough dug out in the sea bottom is really a mountain range under water, with only occasional peaks projecting above the water as islands. In fact the Aleutian Islands are a continuation of the Alaskan Mountains which are part of the Rocky Mountain System, and the range here continues into the sea. If therefore the Aleutian Islands are mountains now in process of formation in the sea, it would seem to follow logically that the Rocky Mountains and Andes, from Alaska to the straits of Magellan, were formed in the same way. What then is the process at work forming the Aleutian Islands?

It is evident that the deep trench south of the islands has been dug out by the expulsion of lava from under the sea and its injection under the Aleutian ridge; this is accomplished by earthquakes, and the process is still in full operation at the present time. This region is a well-known breeding-ground for world-shaking earthquakes and seismic sea waves. Several islands have been uplifted since 1783, and one or more new volcanoes have broken out within

the historical period. The seismic sea waves following the earthquakes which affect this region indicate that the sea bottom often sinks after these disturbances. In other words, when lava is expelled from under the trench and pushed under the adjacent ridge, the bottom gives down to secure stability. The processes now going on have been at work through immense ages, and have thus dug out the trough parallel to the Aleutian Islands, and at the same time elevated this ridge, till it is now partly above the water, thus constituting the chain of islands.

In like manner the great earthquake at Yakutat Bay, farther east, September 3–20, 1899, which was so carefully investigated by Tarr and Martin (*Bulletin of the Geological Society of America*, May, 1906) raised the coast for about 100 miles; the maximum elevation being $47\frac{1}{3}$ feet. Subsidence also occurred in a few places. Such a vast movement of the coast indicates an enormous expulsion of molten rock from beneath the sea under the land. It is these subterranean movements beneath the earth's crust which shake down cities and devastate whole countries. During the earthquake at Yakutat Bay the shaking was so terrible that persons could not stand on their feet; avalanches slid down the mountains, and glaciers were carried into the sea. This is the true nature of earthquakes, and one need not therefore be surprised at the devastation produced. The force which pushes lava under the land, overcoming the weight of the crust, naturally destroys cities and all the frail works of man built upon the surface.

§ 4. *Physical Experiments on the Porosity of Matter.*—Modern science presents many illustrations of the *porosity* of matter. In fact so many experiments illustrate *porosity* that it is difficult to find proof of the general property of *impenetrability* cited by Newton in the "Principia," except under the narrow limitations that the matter in question remains cold and the forces to which it is subjected are small. With increasing fluid pressure and rising temperature all matter is leaky; and in general a rise of temperature expands and thus augments the penetrability and porosity of all substances. *We may therefore say that all matter is porous and leaky under great fluid pressure, and impenetrability does not exist except*

under very restricted conditions, so that it is not a general property of matter as was once supposed.

In the early days of physical science the demonstration of the porosity of such dense bodies as gold, silver and lead was considered a great achievement. In 1661 some academicians at Florence, repeating an earlier experiment of Bacon with a spherical shell of lead, filled a hollow sphere of solid gold with water, and, after sealing it hermetically, flattened the figure of the spherical shell in a hydrostatic press so as to diminish the volume. Under this deformation of the sphere the water was forced through the walls of solid gold and formed in drops on the outside. Corresponding experiments were made with spheres of silver, lead, and other metals, with analogous results. Modern engineering presents innumerable illustrations of the porosity and leaky character of structures made of the hardest bodies. Under great pressure all pipes and pistons leak, and put a limit to the applications of hydrostatic pressure.

In 1883 Amagat forced mercury through plates of solid steel three inches thick, under a pressure of about 4,000 atmospheres. This is the highest pressure hitherto applied in physical experiments, and yet all rocks are subjected to such pressure at a depth of only ten miles below the earth's surface. In the measurement of ocean depths it has been found that empty hollow glass balls with walls half an inch thick sent down with the deep sea apparatus come up more and more completely filled with water, according to the depth of the sea and the duration of the experiment. As glass is the most impervious of solid bodies, this leakage, which it shows under the external application of fluid pressure from the deep sea, is a good illustration of what happens to the bed of the ocean, which is constantly subjected to this pressure. No rock is anything like so impervious as glass, and consequently a general leakage of the ocean bottom inevitably takes place. The water which first enters the bed of the sea will keep on descending till it comes into contact with rock at high temperature, which produces and readily absorbs steam. When the rock becomes saturated with steam it swells and requires more space, and this finally brings on an earthquake. Hence also the preponderance of great earthquakes under the sea and the almost total absence of these disturbances far inland.

§ 5. *Important Criterion for the Nature of the Movement Beneath the Earth's Crust furnished by Seismic Sea Waves.*—In the paper on the "Cause of Earthquakes" we divided seismic sea waves into two general classes: the first, due to the sinking of the sea bottom, and characterized by a withdrawal of the water after the earthquake, to be followed later by the return of a great wave; the second, due to the uplift of the bottom, and characterized by the sudden rise of the sea without any previous withdrawal from the shore. Both classes of these waves exist in our seas, but those of the first class are the most dangerous and the most important. Most of the great historical inundations by the sea have been due to waves of the first class. The phenomena usually noted are: first, a terrible earthquake; second, after a short interval, the sea is noticed to be slowly draining away, laying bare the bottom, where it ordinarily is deep enough to anchor ships; third, after an interval of an hour or so, the sea is seen to be returning as a mighty wave, carrying everything before it, and thus washing the ships inland and stranding them high and dry; fourth, having once swept the shore, the sea again withdraws and lays bare the harbor as before, and after about the same interval again returns as a second great wave. This periodic movement of the sea may be kept up for quite a while, and sometimes quiet is not restored for a day or two.

Among the many well-known historical sea waves of the first class which might be mentioned, we shall cite only a few typical cases: As that which overwhelmed Helike in 373 B. C. (see the paper on the "Temperature of the Earth," § 23, pp. 269–272, and Addendum, pp. 291–298); the wave at Callao in 1746; the wave following the Lisbon earthquake in 1755; the waves of Arica, 1868, and Iquique, 1877; the wave on the Japanese coast in 1896. In all these cases the water first withdrew from the shore; not suddenly, but slowly, as in the draining away of a tide, though somewhat more rapidly; this of course indicated that the sea bottom had sunk, and the water was draining away to fill up the depression in the level caused by the drop of the bottom. When the currents meet at the center an elevation is produced by their mutual impact, and

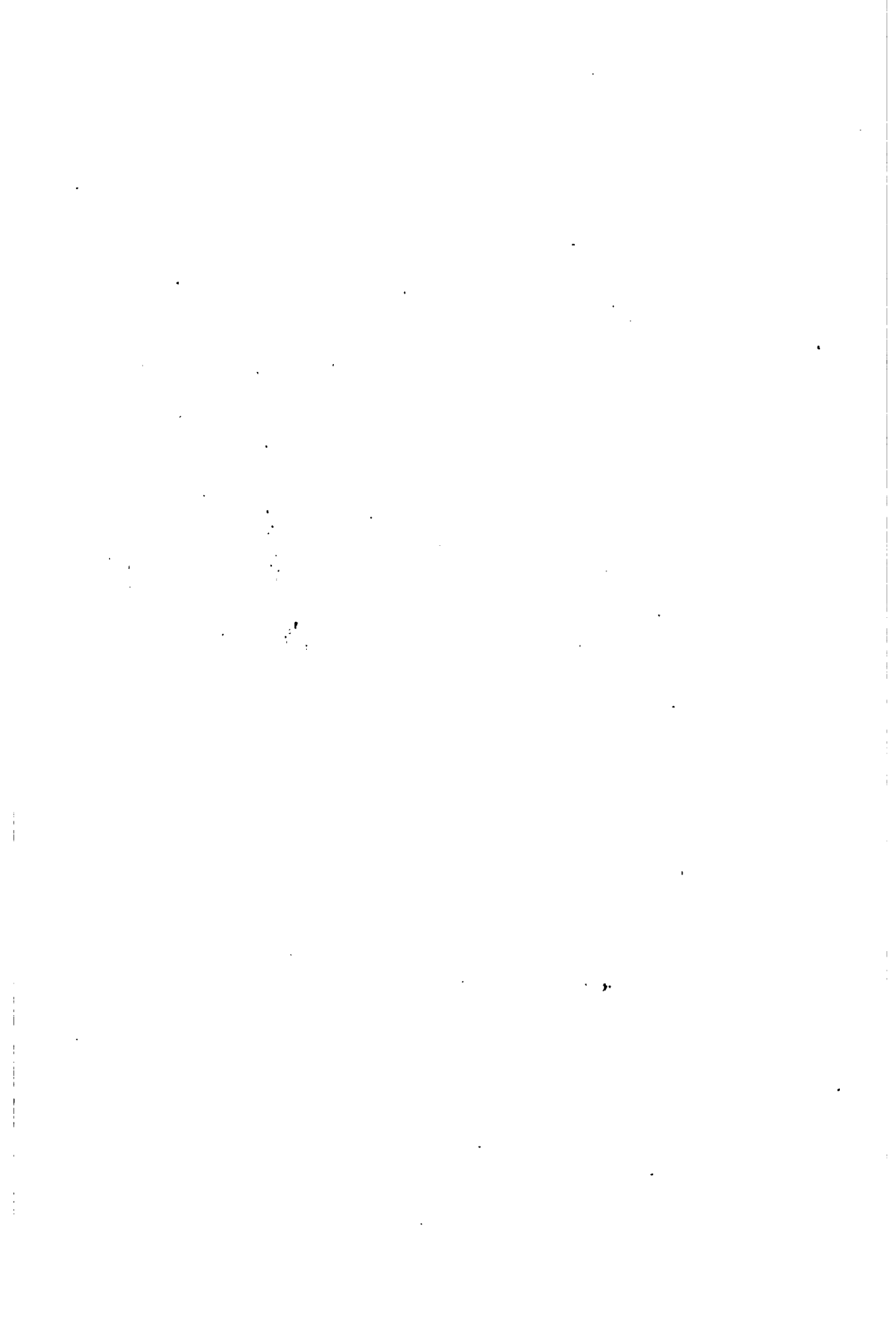
when this collapses under gravity the first great wave comes ashore. The elevation then subsides into a depression as at first, and the currents again flow in and force up the level a second time; and with the second collapse another wave is sent ashore; and so the oscillation of the sea continues, sometimes for a day or two before it finally quiets down.

Now these sea waves of the first class furnish an exceedingly important criterion as to the nature of what is going on beneath the earth's crust. The sinking of the sea bottom often happens in the deep trench south of the Aleutian Islands, and repeated drops of this kind have obviously produced the deep trough parallel to these islands. For it is observed that the earthquake usually raises one or more of the islands to the north, when the sea bottom sinks to the south. Now the islands could not be upraised unless something was pushed under them, and the bed of the trough could not sink down unless it was in some way undermined. Accordingly it follows that molten rock is expelled from beneath the bed of the trough to the south and pushed under the adjacent islands to the north, which are thus uplifted. The bed of the sea often sinks during the earthquake arising from this subterranean movement, and then the water withdraws from the shore and afterwards returns as a great seismic sea wave. It will be observed that the subcrustal movement is from the sea towards the land, because steam accumulates under the ocean, but scarcely at all under the land.

Thus these seismic sea waves become very important criteria for determining whether the sea bottom has sunk; and if it has sunk we know that lava was expelled from under the sea and pushed under the land. Seismic sea waves therefore may be regarded as *very delicate levels*, for determining the movement of the sea bottom; and from the nature of this movement we can often decide what the effect of the earthquake has been. Moreover these waves enable us to tell with certainty that the chief function of earthquakes is the elevation of the land along the coast by the expulsion of lava from beneath the bed of the sea. It is not too much to say that the true nature of earthquakes and their function in the uplift of mountains and plateaus could not be certainly made out except for the exceedingly important criterion furnished by seismic sea waves.

§ 6. *Additional Phenomena Noticed near the Aleutian, Kurile and Japanese Islands, and the Antandes.*—South of the Aleutian chain, as just remarked, a well-known earthquake belt parallels these islands, and the seismic disturbances occurring there are frequently followed by seismic sea waves of the first class. Soon after a great earthquake the water is seen to be withdrawing from the shore, and after a short interval of time it again returns as a mighty wave sweeping everything before it. Many volcanoes have broken out in these islands and several new islands have been uplifted within the historical period. The Russians long ago connected the earthquakes with the volcanoes in the Aleutian Islands. In later years the exact survey of the sea bottom has shown that it is sunk down into a narrow trough right under the earthquake belt. Just parallel to the trough the islands form a real mountain ridge under water, with only a few of the highest points projecting above the surface as islands. The uplift of these islands therefore denotes the uplift of mountain peaks, some of which have become volcanoes.

Now if the earthquakes are accompanied by the uplift of islands and the sinking of the sea bottom, as shown by the seismic sea waves, it follows that the uplift of the ridge is connected with the sinking of the adjacent sea bottom. As the ridge is just contiguous to the trench, and the earth is terribly shaken every time these disturbances occur, it seems to indicate that matter is expelled from under the trench and pushed under the ridge; so that the ridge is elevated and the trench sinks down correspondingly. This could not occur without the bodily transfer of matter beneath the earth's crust, and the shaking of the earth is due to this expulsion of lava from under the trench, and its injection under the ridge. This is the only possible explanation of the observed elevation of the ridge and the sinking of the trench. In this way the trough near the Aleutian Islands has been gradually dug out. Similar troughs have been formed by earthquakes near the Kurile and Japanese Islands, as we know by the observed depth of the sea, the lay of the earthquake belt parallel to these islands, and the occurrence of the seismic sea waves, showing that the sea bottom sinks after the earthquakes by which the region is afflicted. If the islands of Japan were dug off and thrown into the Tuscarora Deep, they would about fill it up.



Therefore all these islands were formed by the expulsion of lava from under the sea, and the subsequent sinking of the sea bottom has given rise to the deep troughs now found in that part of the ocean.

In the same way there is an earthquake belt between Samoa and New Zealand, and the sea bottom is sunk down into a deep trough, parallel to a ridge on the west, on the opposite side of the trench from the ocean. This ridge is a new mountain range 1,200 to 1,500 miles long, now forming on the west of the Pacific, just as the Andes were once formed on the east. Lava is being expelled from under the trench and pushed from the ocean towards the ridge on the west. This is developing into a new mountain range, which we shall call the *Antandes*, because it is being formed opposite to the Andes, on the other side of the Pacific, and in the same manner as the mighty mountains in South America were in earlier geological time. In the course of immense ages the Antandes will rise above the water as a mighty chain on the west of the Pacific just like the Andes on the east.

These phenomena in the sea bottom show the real process of mountain formation at various stages of its progress, and prove to us that most of the folding observed in our mountain ranges now on land really took place in the bed of the sea, long before the whole range was raised above the water. For this sinking and upheaval of adjacent portions of the sea bottom would crumple the rocks exactly as they are observed to be in all mountain ranges; and moreover the several parallel ranges so often observed would result from the development of several parallel troughs, all of which are eventually uplifted. It will be observed that the expulsion of lava is always from the sea towards the land, and this shows that the sole cause of the movement is the leakage of the ocean. It thus follows that mountains, plateaus, and islands are uplifted by earthquakes depending on the leakage of the oceans, and by nothing else.

§ 7. *The Andes with their high Plateaus Merely a Vast Wall Erected by the Pacific.*—It may sound strange to say that the cordillera of the Andes is a vast wall erected by the Pacific Ocean along its border; but to the navigator who traverses the shore from Panama to Cape Horn such a description will seem most appropriate.



FIG. 1. Relief Map of South America. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) Notice that the Andes are a mighty wall erected by the Pacific Ocean along its border. Professor Charles Burkhalter, Director of the Chabot Observatory, Oakland, kindly suggested the use of these relief maps, which are well suited for bringing out the leading characteristics of the different continents.

Throughout the length of the continent the mountains are everywhere parallel to the coast, and run at nearly a constant distance from the shore. The Andes are not always a simple chain, but they are narrow relatively to their height, as compared to the other mountains. In many places there are two or more ranges with narrow plateaus between. These plateaus are so interwoven with the mountains themselves that we may feel sure they were formed together and represent a part of one general movement. Unless this were so it is impossible to believe that so many narrow and high plateaus would be enclosed between mountain walls on either side. The eastern cordillera is less volcanic than the western, and the eastern slope is believed by Professor Solon I. Bailey of Harvard College Observatory, who has exceptional opportunities for judging of these mountains, to be two or three times steeper than the western slope.

If we suppose a sea trough was first dug out in the elevation of the eastern range, and eventually when deep sediments had accumulated in the trough, the western edge of it was folded up to form the western range, and the trough itself became the plateaus, we shall have very nearly a true picture of how the Andes were formed. The full details of this process cannot be given now, but there is no doubt that the Andes are a vast wall erected by the Pacific along the edge of the continent. This origin of these mountains is also indicated by the earthquakes observed within historical time; for the coast has been again and again upraised by these disturbances, while the sinking of the sea bottom, indicated by the accompanying seismic sea waves, shows that the bed of the ocean is being undermined by the expulsion of lava under the land. The shells, fossils, and other evidences of marine life now found at altitudes as high as 15,000 feet show that the uplifting at present going on is but a part of the greater uplift of past geological ages; so that the great movement which formed these mountains and plateaus is identical with the earthquake disturbances noticed within historical time.

§ 8. *The uplift of mountains and plateaus around the margins of the Pacific, and of islands in the interior, with innumerable submarine eruptions everywhere, is nature's way of indicating leakage*

through twenty miles of crust.—The peculiar position of the sea bottom between a molten globe and the overlying ocean is such that any disturbance of the bottom, as in a volcanic eruption, would naturally excite our suspicions that the crust had leaked and brought the water into contact with the underlying ball of fire. The situation of the overlying ocean, with the fire so close beneath, is much the same as that of the water above the furnace of a boiler, in which steam is developed; and if one had the molten globe for a furnace and the ocean for a reservoir of water, leakage would develop steam on a grand scale, and give rise to mighty experiments exactly resembling earthquakes and volcanic eruptions. Some of these disturbances might take the form of uplifts of the crust into islands, mountains and submarine volcanoes, others near the edges of the sea would cause lava to push out under the land and raise the coasts.

Now the Pacific Ocean is everywhere surrounded by high mountains, as if the lava had been pushing out at the margins of the sea. And throughout the interior a vast number of islands are raised up in deep water, and every part of the ocean is from time to time disturbed by terrible earthquakes. One must therefore admit that the ocean has the aspect which might be expected to result from a leakage of the ocean bed. Moreover the Pacific is surrounded nearly everywhere by volcanoes, which emit chiefly vapor of steam. If it is shown that mountains are formed by earthquakes, chiefly in the expulsion of lava under the land, and some of the mountains break out into volcanoes, then there will obviously be a connection not only between earthquakes and volcanoes, but also between the vapor of steam emitted from these smoking mountains and that formed under the ocean by the leakage of the bottom.

It is this intimate connection between all the related phenomena which tells so powerfully in favor of the view that the leakage of the ocean takes place through a layer of rock twenty miles thick. The height of the mountains and plateaus is but a small fraction of the thickness of the crust, and movement in the underlying layers therefore usually gets relief without breaking through. The crust of the globe is thick enough to offer great resistance to uplift, so that the steam saturated lava usually adjusts itself beneath without a surface eruption. Yet where the crust is sharply upheaved as in

mountains, volcanoes sometimes break out. But it is obvious that earthquakes are the more general, volcanoes the more special phenomena; and that both are connected with mountain formation, and depend on the sea for their continued activity.

§ 9. *On the Structure of Granite as a Typical Crystalline Rock of the Earth's Crust.*—Granite has a thoroughly crystalline structure, and is an admixture of feldspar, mica, and quartz. The mica is in the form of minute shingles, or snowflakes, embedded in the non-crystalline matrix of quartz, which encloses the other elements. The feldspar is chiefly orthoclase. The two chief ingredients, quartz and feldspar, form a granular aggregate made up of grains of fairly equal size, varying all the way from several inches in diameter to a structure so fine as to be inseparable to the naked eye.

"Many granites contain irregularly shaped cavities (miarolitic structure), in which the component minerals have had room to crystallize in their proper forms, and where beautifully terminated crystals of quartz and felspar may be observed. It is in these places also that the accessory minerals (beryl, topaz, tourmaline, garnet, orthite, zircon and many others) are found in their best forms. Not improbably these cavities were somewhat analogous to the steam holes of amygdaloids, but were filled with water or vapour of water at high temperature and under great pressure, so that the constituents could crystallise under the most favorable conditions. Among the component minerals of granite, the quartz presents a special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch and to give a milky turbid aspect to the mineral. The liquid in these cavities appears usually to be water, either pure or containing saline solutions, sometimes liquid carbon-dioxide" (p. 143). (Sir A. Geikie, "Geology," p. 204.)

The cavities in crystalline rock such as granite may contain either gas or liquid matter, and sometimes both. Professor Tilden's researches have shown that the included gases (hydrogen, carbon dioxide, carbon monoxide, marsh gas, nitrogen, and water vapor) may exceed many times the volume of the rock itself. The cavities have all manner of forms, branching, oblong, curved, oval, spherical and negative crystalline shapes, and are often so numerous as to give a turbid aspect to the mineral. The intersecting planes of the crystalline granite frequently present real fissures more or less filled with liquid. Obviously capillary forces may here attain great importance, and fluid entering the rock would be absorbed into these spaces

with irresistible power. Geikie remarks that the cavities in quartz have all sizes from the coarse pores visible to the naked eye to minute spaces less than $1/10,000$ of an inch in diameter, which can be seen only under high magnifying power.

Now it is worth while to remember that small as are the least cavities and fissures which we can see with the microscope, they are very large and coarse compared to the molecular structure of a fluid such as water or of a solid like glass. It is useful to remember that the limit of naked eye vision is about $1/250$ of an inch, and of the most powerful microscope about $1/100,000$ of an inch. The microscope therefore increases our power of vision about 400 times. (Cf. Prof. A. A. Michelson's "Light Waves and their Uses," p. 30.)

§ 10. *On Lord Kelvin's Determination of the Size of Atoms.*—In order to form a clear conception of the physical constitution of the matter composing the crust of the globe, we must recall the lines of research by which Lord Kelvin has determined the size of atoms.

1. By determining the work done or heat produced in bringing thin plates of zinc and copper together. The observed amount of heat evolved when the plates are made of given thickness and afterwards imagined to be thinner and thinner, limited only by the condition that the mass shall not be melted, under the heat of combination, which is not indefinitely great even when brass is produced by fusing zinc and copper, but corresponds to the mutual attraction of a number of plates not more numerous than 100,000,000 to the millimeter; hence it follows that the molecules are at least $1/1,000,000,000$ cm. and probably more than $1/400,000,000$ cm. in diameter. Lord Kelvin concluded that "Plates of zinc and copper $1/300,000,000$ of a centimeter thick, placed close together alternately, form a near approximation to a chemical combination if indeed such thin plates could be made without splitting atoms." He fixed $1/1,000,000,000$ of a centimeter as the minimum diameter of the atoms found in this way. It is to be remembered here that 2.54 centimeters = 1 inch.

2. By the study of Newton's rings on soap bubbles as they become thinner and thinner, the thickness of the film being reckoned from the known wave-length of the reflected light. Unless the film materially weakened when a certain limit is attained, it could not be stretched beyond a certain thickness without volatilizing, if

maintained at the same temperature; for as it expands it cools, and the heat that would have to be supplied to it would be more than sufficient to vaporize it. Now it is found by observation that the intensity of the surface tension of the film of water falls off before the thickness is reduced to $1/200,000,000$ cm., and hence there probably are but few molecules in that thickness.

3. By the phenomenon of dispersion in the wave theory of light. Cauchy showed that dispersion of colors implied a granular structure in refracting media, and that the grains could not be indefinitely small, but must exceed $1/10,000$ of the shortest wave length; and to produce the observed effect Lord Kelvin concluded that the number of molecules in a wave length would have to be from 200 to 600. Nobert ruled lines on glass at the rate of 40,000 to the centimeter,² or about two to the wave length of blue light (about $4/100,000$ centimeter); and as this left the ruled surface capable of reflection, the number of molecules in the ridges between the grooves must have been sufficient to give solid body to the sculptured mass, and thus not less than several hundred to the wave length. If the mean free path in a solid like glass be 25 times the diameter of the atom itself, this will make the diameter of the atoms of the order of $1/400,000,000$ of a centimeter.

4. By calculating the length of the average free path of a molecule in a gas, according to the kinetic theory. Loschmidt in 1865, Stoney in 1866, and Lord Kelvin in 1870, independently reached similar results, namely, for the average free path about $1/100,000$ of a centimeter, and for the diameter of the gaseous molecule about $1/500,000,000$ of a centimeter.

These four methods of estimating the diameter of atoms thus agree very closely among themselves; and moreover a similar result on the average distance of molecules deduced by entirely different

² Referring to Nobert's lines Maxwell says: "A cube, whose side is the 400th of a millimetre, may be taken as the *minimum visible* for (microscopic) observers of the present day. Such a cube would contain from 60 to 100 million molecules of oxygen or nitrogen" (cf. The article "Atom," *Encyclopaedia Britannica*, ninth edition, p. 42). If there be 400 molecules in a line the length of the edge of the cube just considered, the cube would contain 64,000,000, which agrees with Maxwell's estimate. A line equal to the wave length of blue light would thus contain 250 molecules.

considerations was obtained by M. Lippmann, in a paper read to the Paris Academy of Sciences, October 16, 1882.

In his "Popular Lectures and Addresses" (vol. 1, p. 224) Lord Kelvin condenses his conclusions as follows:

"The four lines of argument which I have now indicated lead all to substantially the same estimate of the dimensions of molecular structure. Jointly they established, with what we cannot but regard as a very high degree of probability, the conclusion that, in any ordinary liquid, transparent solid, or seemingly opaque solid, the mean distance between the centres of contiguous molecules is less than the $1/5,000,000$ and greater than the $1/1,000,000,000$ of a centimeter.

"To form some conception of the degree of coarse-grainedness indicated by this conclusion, imagine a globe of water or glass, as large as a football,¹ to be magnified up to the size of the earth, each constituent molecule being magnified in the same proportion. The magnified structure would be more coarse grained than a heap of small shot, but probably less coarse-grained than a heap of footballs."

§ 11. *On the Molecular Constitution of Matter and on the Penetrability of Solids by Fluids.*—In his address on "Mathematical Physics" at the St. Louis Congress of Arts and Sciences in 1904, Poincaré speaks of the porosity of matter as follows:

"The astronomical universe consists of masses, undoubtedly of great magnitude, but separated by such immense distances that they appear to us as material points; these points attract each other in the inverse ratio of the squares of their distances, and this attraction is the only force which affects their motion. But if our senses were keen enough to show us all the details of the bodies which the physicist studies, the spectacle thus disclosed would hardly differ from the one which the astronomer contemplates. There too we should see material points separated by intervals which are enormous in comparison with their dimensions, and describing orbits according to regular laws. Like the stars proper, they attract each other or repel, and this attraction or repulsion, which is along the line joining them, depends only on distance." (Cf. *Bulletin of the American Mathematical Society*, February, 1906, p. 241; authorized translation by Professor J. W. Young.)

Professor Sir G. H. Darwin's recent presidential address to the British Association for the Advancement of Science at Cape Town, 1905, was devoted largely to the discovery of electrons. After treating of these subatomic corpuscles he adds:

"I have not as yet made any attempt to represent the excessive minuteness of the corpuscles, of whose existence we are now so confident; but, as an introduction to what I have to speak of next, it is necessary to do so.

¹ Or say a globe of 16 centimeters diameter.

To obtain any adequate conception of their size we must betake ourselves to a scheme of threefold magnification. Lord Kelvin has shown that if a drop of water were magnified to the size of the earth the molecules of water would be of a size intermediate between that of a cricket ball and of a marble. Now each molecule contains three atoms, two being of hydrogen and one of oxygen. The molecular system probably presents some sort of analogy with that of a triple star; the three atoms replacing the stars, revolving about one another in some sort of a dance which cannot be exactly described. I doubt whether it is possible to say how large a part of the space occupied by the whole molecule is occupied by the atoms; but perhaps the atoms bear to the molecule some such relationship as the molecule to the drop of water referred to. Finally, the corpuscles may stand to the atom in a similar scale of magnitude. Accordingly, a threefold magnification would be needed to bring these ultimate parts of the atom within range of our ordinary scales of measurement. . . .

"The community of atoms in water has been compared with a triple star, but there are others known to the chemists in which the atoms are to be counted by fifties and hundreds, so that they resemble constellations."

Such general discussions by these illustrious physicists, Kelvin,¹ Poincaré and Darwin, are not to be construed too literally, and yet they clearly indicate the general belief among the foremost men of science that the spaces between the particles of matter are immense in comparison with the dimensions of the particles themselves.

From Lord Kelvin's discussion of the size of atoms treated in the above section, we have seen that the diameters of these bodies is of the order of $1/500,000,000$ of a centimeter, or $1/1,270,000,000$ of an inch. The average space between the molecules being $1/100,000$ of a centimeter, or about 5,000 times the diameter, is of the order of $1/254,000$ of an inch. This is decidedly below the

¹ In a well-known paper on gravitating matter, Lord Kelvin compares the stars of the Milky Way to the atoms of a bubble of gas. For a giant for whom our suns would be what atoms are to us, the stars would be beyond the reach of the keenest vision and the Milky Way appear to behave as a gaseous medium. M. Poincaré has discussed the problems of the universe from this point of view in an address to the Astronomical Society of France (*Bulletin Astronomique de la Société Astronomique de France*, April, 1906; an excellent translation in *Popular Astronomy* for October, 1906). It is remarkable that Democritus, founder of the atomic theory among the Greeks (460-360 B. C.), should also have recognized that the Milky Way is composed of a mass of stars too dense to be seen separately by the unaided vision (cf. "Aristotle's Meteorology," Lib. I., Ch. VIII., Sec. 4). Thus Lord Kelvin's conceptions do not differ greatly from those of Democritus of Abdera, though the modern theories are much better established than the atomic theories were among the Greeks.

limit of resolution of the microscope which has been estimated by Michelson at $1/100,000$ of an inch.

Now in our discussion of the constitution of granites we found that the *visible pores* in the quartz matrix have all diameters down to less than $1/10,000$ of an inch, and thus practically to the lowest limit visible in the microscope. These visible pores thus evidently connect directly with the smaller invisible spaces which separate the molecules. As the diameters of the molecules in water vapor are only about $1/5,000$ of the spaces between them, the triple atom of hydrogen and oxygen constituting water or water vapor would have ample facilities for penetrating a spongy and cavernous mass like granite with innumerable holes frequently of large size but always at least equal to the average free path. If the water or vapor were under pressure, so as to condense the fluid and thus increase the number of vibrations of a molecule per second, the rate of penetration of the fluid obviously would be much augmented.

And since granite not only is filled with pores of these various sizes, but also everywhere more or less cleft by planes of crystalline structures which are not really tight, but full of fissures and thus inviting the penetration of the fluid by the full power of capillary forces, we see that water would necessarily penetrate it at a fairly rapid rate. At the same time the influence of capillarity in such a structure is so great that although water might enter and slowly pass through it, even the development of steam pressure beneath the layer would not force the fluid back, because the steam pressure is nullified an infinitely small distance from where it is exerted, on account of capillary resistance; yet the fluid may keep on descending under the suction of the capillary forces so long as the supply from above is not cut off.

Upon these physical grounds it seems clear that there must be a secular leakage of the ocean bottoms, and a corresponding development of steam beneath the earth's crust. The steam expands the rock in which it is absorbed and in seeking release thus brings on earthquakes and mountain formation.

Even if the pressure due to depth should tighten up the structure of the rock in the lower layers of the crust, it would not be able to obliterate the leakage depending on the pores and crystalline

structure. It is evident that at depths such as twenty miles the downward movement of the fluid would continue, though very slowly. Hence the leakage of the oceans is extremely gradual, and the recurrence of earthquakes visibly delayed after relief has once been obtained. Thus while the tightness of the earth's crust due to the grain of the rock and the pressure to which it is subjected in the lower parts does not prevent ocean leakage, it makes the process so slow and gradual as to afford considerable protection to life upon our planet.

II. ON THE PHYSICAL STATE OF THE EARTH'S INTERIOR, ON THE AVERAGE RIGIDITY OF THE GLOBE AS A WHOLE, AND ON THE SUBSTRATUM OF PLASTIC MATTER BENEATH THE CRUST WHICH IN EARTHQUAKES BEHAVES AS FLUID.

§ 12. *On the Theory of a Fluid Globe Held by the Older Geologists, and on Hopkins' Argument for Solidity Based on the Phenomena of Precession and Nutation.*—In the early part of the nineteenth century it was generally believed by geologists that the earth was a liquid globe covered by a rocky crust much thinner in proportion to the diameter than the shell is to that of an egg. This supposed liquid interior had been suggested by the streams of molten lava often observed to issue from volcanoes, and by the igneous rocks so abundantly poured forth in many places. The theory of a fluid globe seemed to be confirmed by the observed increase of temperature downward, which would give rise to molten rock at a depth of some twenty miles. The mountains and other phenomena traceable to dislocations of the crust could all be explained by a solid layer of this thickness, and the natural inference was that the great central nucleus remained liquid. The consolidation of the globe was ascribed to the progress of secular cooling, from the primitive state of high temperature assumed by Laplace in the nebular hypothesis postulated for explaining the origin of the solar system.

The older geologists had not adequately considered the effects of pressure in augmenting the solidity of the globe as we go downward; for since pressure raises the melting point of solids, the matter of the nucleus, though highly heated, might be solid if the

pressure be great enough to prevent fusion under the prevailing temperature. In order to throw light upon this question, Hopkins of Cambridge, England, took up the problem in 1839 (*Phil. Trans.*, 1839; "Researches in Physical Geology," 1839-1842), and sought to prove from the observed phenomena of precession and nutation that the earth could not be composed of a thin shell some twenty miles thick, filled with liquid. He concluded that the crust could not be less than 800 to 1,000 miles thick, and that the globe might even be solid to the center, except some small vesicular spaces here and there filled with molten rock.

In 1868 this subject was examined by the eminent French astronomer, Delaunay, who published a paper on "The Hypothesis of the Interior Fluidity of the Globe" (*C. R. Acad. des Sci.*, Paris, July 13, 1868), in which he threw doubt on the views of Hopkins, and suggested that if the earth's nucleus were a mass of sufficient viscosity it might behave as if it were solid, and hence concluded that the observed phenomenon of precession and nutation did not necessarily exclude a fluid nucleus.

§ 13. *Lord Kelvin's Earliest Studies on the Precession of a Spheroid Containing Liquid.*—Lord Kelvin had already taken up the problem of the internal state of the earth in 1862, and considered the effects of a fluid nucleus enclosed in a thin shell when the whole mass was subjected to tidal strains. As the shell must yield under these strains the land would be carried up and down with the superjacent sea, and if such yielding occurred it ought to be sensible to observation. But since the sensible obliteration of the tides had not been observed, he naturally inclined to the view of Hopkins that the earth is effectively rigid and behaves as a solid globe.

In reply to Delaunay's criticism Lord Kelvin pointed out that if the French astronomer had worked out the problem mathematically he could not fail to see that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, he attributes to the earth as a whole." (*Nature*, February 1, 1872.) On making this calculation Lord Kelvin found that the earth's crust down to depths of

hundreds of kilometers must be capable of resisting a tangential stress of nearly 0.1 of a gramme weight per square centimeter; this would rapidly draw out of shape any plastic substance which could be properly called a viscous fluid. "An angular distortion of 8" is produced in a cube of glass by a distorting stress of about ten grammes weight per square centimeter. We may therefore safely conclude that the rigidity of the earth's interior or substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen yearly nutation." (*Nature*, February 1, 1872, p. 258.)

Notwithstanding these early criticisms of Delaunay's paper, Lord Kelvin subsequently concluded that the phenomena of precession and nutation do not decisively settle the question of the earth's internal fluidity. Yet the semiannual and lunar fortnightly nutations may be considered to disprove absolutely the existence of a thin rigid shell full of liquid. If the fluid were arranged in successive layers of equal density, the only nutational or precessional influence exerted upon it would depend on the non-sphericity of the shells. "A very slight deviation of the inner surface of the shell from perfect sphericity would suffice," according to Lord Kelvin, "in virtue of the quasi-rigidity due to vortex motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body." (Sir W. Thomson, *British Assoc. Report*, 1876, Sections, p. 5.)

It will be seen from this discussion that the argument from precession and nutation is only in part conclusive. If the fluid had a viscosity approaching high rigidity for rapidly acting forces, or it were subjected to such pressure that the particles in confinement acquired the properties of a solid, there would evidently be no sensible deviation from the precession and nutation appropriate to a cold solid globe.

§ 14. *On Lord Kelvin's Researches on the Earth's Rigidity Based on the Analysis of the Tides.*—The state of the earth's interior had early engaged the attention of Lord Kelvin, for the propagation of heat through the crust was before him as early as

1846. ("De Motu Caloris per Terræ Corpus," read before the faculty of the University of Glasgow in 1846; also a "Note on Certain Points in the Theory of Heat," February, 1844, published in the *Cambridge Mathematical Journal*, and reprinted in the "Mathematical and Physical Papers of Sir W. Thomson," 1882, Vol. I, Art. X.)

In a paper "On the Rigidity of the Earth" published in the *Philosophical Transactions of the Royal Society* for May, 1862, Lord Kelvin pointed out that if the matter of the earth's interior yielded readily to the tidal forces arising from the attraction of the sun and moon, the crust itself would respond to these forces in much the same way as the waters of the sea; and the corresponding movements of the crust would mask or largely reduce the height of the oceanic tides calculated for a rigid earth. By actual analysis of long series of tidal observations Kelvin and Darwin subsequently found the observed fortnightly tide to have very nearly its full theoretical height, and hence concluded that our globe as a whole possesses a very high effective rigidity. (Cf. Thomson and Tait's "Natural Philosophy," Vol. I, part II, § 832-847; also the article "Tides," *Encyclopædia Britannica*, ninth edition, § 44.)

Owing to the great importance of this work on the rigidity of the earth, we must trace the successive steps in the advancement of our knowledge. The assumption that the earth is made up of a liquid nucleus covered with a thin crust stiff enough to maintain its figure against the tide-raising forces of the sun and moon would imply that the crust has a degree of strength and rigidity not possessed by any known substance. It was therefore inferred by Lord Kelvin as early as 1862 that the crust might be 2,000 to 2,500 miles thick, in order to resist distortion under the tide-producing forces arising from the sun and moon.

"If the crust yielded *perfectly*, there would be no tides of the sea, no rising and falling relatively to the land, at all. The water would go up and down with the land, and there would be no relative movement; and in proportion as the crust is less or more rigid the tides would be more or less diminished in magnitude. Now we cannot consider the earth to be absolutely rigid and unyielding. No material that we know of is so. But I find from calculation that were the earth as a whole not more rigid than a similar globe of steel the relative rise and fall of the water in the tides would be only

two-thirds of that which it would be were the rigidity perfect; while, if the rigidity were no greater than that of a globe of glass, the relative rise and fall would be only two-fifths of that on a perfectly rigid globe.

"Imperfect as the comparison between theory and observation as to the actual height of the tides has been hitherto, it is scarcely possible to believe that the height is only two fifths of what it would be if, as has been universally assumed in tidal theories, the earth was perfectly rigid. It seems, therefore, nearly certain, with no other evidence than this afforded by the tides, that the tidal effective rigidity of the earth must be greater than that of glass. This is the result taking the earth as a globe uniformly rigid throughout. That a crust fifty or a hundred miles thick could possess such preternatural rigidity, as to give to the mass, part solid and part liquid, a rigidity as a whole, equal to that of glass or steel is incredible; and we are forced to the conclusion that the earth is not a mere thin shell filled with fluid, but is on the whole or in great part solid." (Paper read to Geological Society of Glasgow, February 14, 1878; Kelvin's "Popular Lectures and Addresses," Vol. II, pp. 317-318.)

In his presidential address to the Mathematical and Physical section of the British Association at Glasgow, September 7, 1876, Lord Kelvin remarked of the earth's crust that "were it of continuous steel and 500 kilometers thick, it would yield very nearly as much as if it were india rubber to the deforming influences of centrifugal force and of the sun's and moon's attractions." "The solid crust would yield so freely to the deforming influence of sun and moon that it would simply carry the waters of the ocean up and down with it, and there would be no sensible rise and fall of water relatively to the land." ("Popular Lectures," Vol. II., pp. 251-2.)

Lord Kelvin's final conclusion was that "the earth as a whole is certainly more rigid than glass, but perhaps not quite so rigid as steel."

§ 15. *Darwin's Researches on the Tidal Method of Evaluating the Earth's Rigidity.*—As the natural successor of Lord Kelvin in the researches on the physics of the earth, Professor Sir G. H. Darwin took up the problem of the earth's internal physical condition and confirmed and extended these conclusions by several important lines of inquiry. Darwin's researches on the bodily tides of viscous and semi-elastic spheroids and on the oceanic tides upon a yielding nucleus tended to strengthen the argument for a high effective rigidity so decidedly that he concluded that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition."

But whilst Darwin's researches confirmed Kelvin's conclusions as to the great effective rigidity of the earth, yet a more critical

examination of the method for calculating the fortnightly tide led to the conviction that Laplace's argument is regard to the effects of friction was unsatisfactory. That friction would greatly effect the motion of the water in slow ocean currents within a few days was seen to be untenable. In consequence of this defect it turned out that long period tides as short as a fortnight would not enable the physicist to evaluate the rigidity of the earth, though the 18.6 yearly tide, depending on the revolution of the Moon's nodes, if it can be determined by observation, will eventually give the desired result. The height of this 18.6 yearly tide, however, is only one third of an inch at the equator, and great accuracy will be required for its detection.

Acting on the old belief Darwin compared the lunar fortnightly and monthly tides observed for 33 years at various Indian and European ports, with the equilibrium theory, and found that the tide-heights were about two thirds of the theoretical height. Accordingly he remarks: "On the whole we may fairly conclude that, whilst there is some evidence of a tidal yielding of the earth's mass, that yielding is certainly small, and the effective rigidity is at least as great as that of steel." (Thomson and Tait's "Nat. Phil.," Vol. 1, Part II, § 848.)

This was written prior to the discovery of the theoretical defect in the method of calculating the height of tides with periods not exceeding a fortnight in duration; yet even after the discovery of this defect it was still possible to infer that tides of long period in oceans such as ours must conform much more nearly to the equilibrium laws than do the tides of short period. "Whilst, then, this precise comparison with the rigidity of steel falls to the ground, the investigation remains as an important confirmation of Thomson's conclusion as to the great effective rigidity of the earth. . . . It appears by numerical calculation on viscous and elastico-viscous tides that in order that the oceanic semi-diurnal tide may have a value equal to two thirds of the full amount on a rigid globe, the stiffness of the globe must be about twenty thousand times as great as that of pitch at freezing temperature, when it is hard and brittle." (Sir G. H. Darwin, article "Tides," Ency. Brit., §§ 44-45.)

§ 16. *On the Rigidity of the Earth as found by Comparing the*

Observed Period of the Polar Motion Arising in the Variation of Latitude with the Theoretical Eulerian Period Calculated for a Rigid Earth.—The detection of the variation of latitude by Küstner at Berlin in 1890–91 and the subsequent discussion by Chandler of long series of observations showing that the movement of the pole in the body of the earth has a period of some 427 days, instead of the 305 days long ago inferred from Euler's theory of the rotation of a rigid spheroid, led Professor Newcomb to point out that this observed prolongation of the theoretical Eulerian period indicates some yielding of the matter of the globe under the stresses to which it is subjected by the movement of the pole, and would afford a new method of evaluating the earth's rigidity. In his well-known paper on the "Dynamics of the Earth's Rotation" (*Monthly Notices, R. A. S.*, March, 1892) Newcomb showed that the results already obtained decidedly confirmed Darwin's conclusion that the rigidity of the globe as a whole is comparable to that of steel.

The essential point in Newcomb's explanation is that when the pole changes its position in the body of the globe, the distribution of centrifugal force shifts with respect to the solid earth, which is thus put into a state of stress and must yield to the forces acting upon it, like any other elastic solid body; the periodic deformation of the earth's figure operating to lengthen the period of the free nutation, by an amount depending on the average rigidity of the whole earth.

The continued investigation of the variation of latitude carried out at the various international latitude observatories by Albrecht and others confirms this observational result, and the subject has also been examined theoretically by Darwin, Hough, Larmor and others; so that the validity of the method suggested by Newcomb is generally recognized.

In 1896 Mr. S. S. Hough treated of the problem in a very thorough manner in his well-known paper, "On the Rotation of an Elastic Spheroid" (*Phil. Trans., A*, 1896). He considered chiefly the case of an incompressible homogeneous spheroid, and was enabled to show by rigorous methods that the rigidity of the earth in all probability slightly exceeds that of steel.

In a remarkable paper "On the Period of the Earth's Free

Eulerian Precession," read to the Cambridge Philosophical Society, May 25, 1896, Professor Larmor showed how to estimate the effect of the elastic yielding of a rotating solid on the period and character of the free precession of its axis of rotation, and again confirmed the high effective rigidity of the earth from another point of view.

The observed prolongation of the Eulerian period is thus fully explained by the imperfect rigidity of the earth's mass, and the high rigidity thus deduced has naturally strengthened the earlier conclusions of Kelvin and Darwin drawn from the study of the long period tides of the sea.

This investigation, like those already cited, gives us only an average effect for the earth as a whole, but does not tell us the law of the distribution of rigidity within the globe. If this law of distribution of rigidity could be found, even approximately, it would be of great interest, because we could then see in what part of the globe the principal part of the yielding takes place; and this would give us a much better understanding of the internal constitution of our planet than heretofore has been considered possible.

§ 17. *Rigidity of the Earth Calculated from the Theory of Gravity, on the Hypothesis that the Distribution of Rigidity in the Globe is Everywhere Proportional to the Pressure.*—It has not been supposed by previous investigators that a method could be devised for deducing the rigidity of a body like the earth from the theory of gravity; but in 1905 it occurred to the present writer that such a method could be found if we could adopt a suitable hypothesis for the variation of the rigidity with the pressure. Previous investigations of the internal state of the heavenly bodies had justified the law of Laplace as giving an excellent approximation to the law of density for the earth and the rest of the encrusted planets; and the monatomic law had been found most satisfactory for the sun and fixed stars (cf. *A. N.*, 4053). These laws enable one to obtain the pressure at every point of the radius of the heavenly bodies. For in several ways Laplace's law of density is fairly well established for the earth, and on equally good grounds the density of the sun is believed to conform essentially to the monatomic law.

From a study of the laws of density, pressure and temperature within the heavenly bodies it appeared to me (as it had indepen-

dently appeared to Arrhenius five years before) that matter under these extreme conditions must be essentially gaseous; and as it is above the critical temperature, it is made to behave in confinement as an elastic solid. Now in all gaseous masses the density is proportional to the pressure so long as the gas remains perfect; and the gas does not cease to be perfect when the temperature is above the critical value, though it may acquire in confinement the property of an elastic solid if the pressure be great enough to bring the molecules within a distance at which the molecular forces become effective in spite of the high temperature. Thus while the property of rigidity in cold solids depends wholly on molecular forces which prevent deformation, this property for gaseous matter in confinement under such pressure that it acquires the property of an elastic solid, is due wholly to the pressure. The molecular forces giving effective rigidity must increase in proportion to the pressure, or in a higher ratio.

If according to hypothesis the matter is made solid by pressure, then the molecular forces resisting deformation in the imprisoned matter thus solidified cannot resist deformation in a less degree than the direct proportion to the pressure on which the solidification depends. And any ratio higher than the direct proportionality to the pressure would most likely depend on the temperature. Now the temperature in the earth is supposed to be everywhere such as to make the density conform essentially to Laplace's law; and the pressure resulting from this law of density gives the matter everywhere the property of an elastic solid, and therefore its molecular properties must correspond to the physical state determined by the laws of density and pressure.

It is of course conceivable that some parts of the globe might be relatively more rigid than is required to give solidity, but the effect of this would only increase the average rigidity of the earth as a whole. And since seismological and other observations seem to show that the globe is solid throughout, except a thin layer just beneath the crust, the hypothesis of a rigidity proportional to the pressure will give a true minimum value of the earth's rigidity.

Now on the hypothesis that the density follows Laplace's law,

the pressure throughout the earth's mass is given by the formula (cf. *A. N.*, 4104)

$$p = \frac{3x}{2(\sigma_1 g)q^2} [(\sigma g)^2 - (\delta g)^2], \quad (1)$$

where r is the radius of the earth, g mean gravity, q the constant for Laplace's law, 2.52896 radians $= 144^\circ 53' 55''.2$, σ the density at any point, δ the density at the surface, and σ_1 the mean density.

To render this expression available for integration throughout the sphere occupied by the earth's mass, we must put for σ^2 its value

$$\sigma^2 = \sigma_0^2 \frac{\sin^2(qx)}{q^2 x^2},$$

and for δ^2 its value

$$\delta^2 = \sigma_0^2 \frac{\sin^2 q}{q^2},$$

corresponding to the surface where $x = 1$. Thus we obtain

$$p = \frac{3(\sigma_0 g)^2 r}{2(\sigma_1 g)q^2} \left[\frac{\sin^2(qx)}{q^2 x^2} - \frac{\sin^2 q}{q^2} \right]. \quad (2)$$

For the total pressure throughout a sphere of radius $\rho = rx$, r being the external radius, and $x = (\rho/r) =$ fraction of the radius, we have

$$\begin{aligned} P &= \int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx \\ &= \frac{3(\sigma_0 g)^2 \cdot r 4\pi r^3}{2(\sigma_1 g)q^4} \left(\int_0^x \frac{\sin^2(qx)}{x^2} x^2 dx - \sin^2 q \int_0^x x^2 dx \right), \end{aligned} \quad (3)$$

which by integration becomes

$$P = \frac{3(\sigma_0 g)^2 r 4\pi r^3}{2(\sigma_1 g)q^4} \left(\frac{qx - \sin(qx) \cos(qx)}{2q} - \sin^2 q \frac{x^3}{3} \right). \quad (4)$$

As our integration is to include the whole sphere of the earth, we put $x = 1$, and then we have

$$P = \frac{3(\sigma_0 g)^2 \cdot r 4\pi r^3}{2(\sigma_1 g)q^4} \left(\frac{q - \sin q \cos q}{2q} - \frac{\sin^2 q}{3} \right). \quad (5)$$

The total volume of the earth is $(4/3)\pi r^3$, and hence the average pressure per unit of area on all concentric spherical surfaces is

$$R = \frac{P}{\frac{4}{3}\pi r^3} = \frac{3}{4\pi r^3} \int_0^a p \cdot 4\pi r^2 x^2 \cdot r dx \quad (6)$$

$$= \frac{9(\sigma_0 g)^2 \cdot r}{2(\sigma_1 g) q^4} \left(\frac{q - \sin q \cos q}{2q} - \frac{\sin^2 q}{3} \right).$$

If r is expressed in meters, the mean pressure or mean rigidity R comes out in kilograms per square meter. To reduce the result to atmospheres we divide by 10,333. The result for the earth is $R = 748,843$ atmospheres, about the rigidity of wrought iron.

This method takes no account of the earth's solid crust, and is therefore too small; moreover viscosity increases within the earth, owing to the rise of temperature downward. We give hereafter an approximation to the increase of rigidity by determining the mean rigidity of the earth's *matter*, as distinguished from that of the *various layers* composing the globe, just found by the above analysis.

To find the mean rigidity of the earth's *matter* we must consider not only the pressure but also the density or mass per unit volume of the imprisoned matter in each layer. The result represents a mean rigidity in which every elementary spherical shell composing the globe is allowed a weight proportional to its mass, which is multiplied by the pressure to which it is subjected.

The theory of the determination of the mean rigidity of the earth's matter is as follows:

$$P' = \int_0^a p \cdot 4\pi r^2 x^2 \cdot r dx \cdot \sigma = 4\pi r^3 \sigma_0 \int_0^a p \cdot x^2 dx \frac{\sin(qx)}{qx}. \quad (7)$$

Substituting for p its value from (2), we get

$$P' = \frac{3(\sigma_0 g)^2 \cdot r \cdot 4\pi r^3 \sigma_0}{2(\sigma_1 g) q^5} \left(\int_0^a \frac{\sin^3(qx) x^2 dx}{x^3} - \sin^2 q \int_0^a \frac{x^2 \sin(qx) dx}{x} \right), \quad (8)$$

$$= \frac{3(\sigma_0 g)^2 \cdot r \cdot 4\pi r^3 \cdot \sigma_0}{2(\sigma_1 g) q^5} \left(\int_0^a \frac{\sin^3(qx) q dx}{qx} - \sin^2 q \int_0^a \frac{x \sin(qx) q dx}{q} \right). \quad (9)$$

The integral of this last term is $-\sin^2 q \frac{\sin(qx) - qx \cos(qx)}{q^2}$.

The value of the first integral is most conveniently found by quadrature, table for which is given in *A. N.*, 4104, p. 379. Dividing out the mass, or volume of the sphere by the density, we have

$$\begin{aligned}
 R' &= \frac{P}{\frac{4}{3}\pi\sigma_1 r^3} = \frac{3 \int_0^x \rho \cdot 4\pi r^2 x^2 \cdot r dx \cdot \sigma}{4\pi\sigma_1 r^3} \\
 &= \frac{9(\sigma_0 g)^2 \cdot r \cdot \sigma_0}{2(\sigma_1 g) q^3 \sigma_1} \left(\int_0^x \frac{\sin^3(qx) q dx}{qx} - \frac{\sin^2 q}{q^3} [\sin(qx) - qx \cos(qx)] \right).
 \end{aligned} \tag{10}$$

On putting $qx = 144^\circ 53' 55''.2$, the value of the integral is found by quadrature to be 0.9592502, and when the rest of the formula is reduced to numbers we have (*A. N.*, 4104) :

$$R' = 1028702 \text{ atmospheres.}$$

The rigidity of nickel steel is taken to be 1,000,000 atmospheres. It thus appears from this calculation that the average rigidity of all the earth's matter somewhat exceeds that of nickel steel. The actual rigidity of the earth almost certainly lies between the limits thus established, namely $R = 748,843$, based on the rigidity of the layers deduced from the pressure to which they are subjected, and $R' = 1,028,702$, derived from the product of the mass of each layer by the pressure acting upon it.

In the paper, "Researches on the Rigidity of the Heavenly Bodies," *A. N.*, 4104, the rigidity of the earth is discussed as follows :

"When one considers the effects of the enclosing crust and the viscosity of the whole earth, which must be assumed to increase towards the centre, owing to the increasing density and rising temperature of the imprisoned matter, it seems not improbable that the actual effective rigidity of our globe may be nearer the upper limit than the lower, and probably we shall not be far wrong in concluding that it is approximately equal to that of nickel steel.

"Leaving aside the consideration of the effects of the solidified crust, it is evident from the nature of the forces at work that most of the yielding of our globe, due to the periodic action of small forces, is in the outer layers; and in general the yielding in any concentric layer may be taken to be inversely as the pressure to which the imprisoned matter is subjected. *It is remarkable that the curve of pressure as we descend in the earth becomes therefore also the curve of effective rigidity for the matter of which the earth is composed.* Thus the rigidity of the matter at the earth's center probably is at least three times that of nickel steel used in armor plate; as we approach the surface the effective rigidity constantly exceeds that of nickel steel until we come within less than 0.4 of the radius from the surface, where the pressure is less than 1,000,000 atmospheres.

"To imagine a mechanical substitute for the earth's constitution, without the introduction of pressure, suppose an alloy of adamant to give the material at the centre of such a globe, of the same size but devoid of gravitation, a hardness three times that of armor plate. The outer layers as we approach the surface must then be supposed softer and softer, until it is like armor plate at a little over 0.6 from the center, and finally a very stiff fluid near the surface. In addition to this arrangement of its effective internal rigidity the actual earth is enclosed in a spheroidal shell of solid rock analogous to granite. One can easily see that tidal forces applied to all the particles of such an artificial armored sphere would produce but very slight deformation, because of the enormous effective rigidity of the nucleus.

"The principal uncertainty in this result arises from the admissible variations in the assumed Laplacean distribution of density within the earth. Both Radau and Darwin (cf. *Monthly Notices*, Roy. Astron. Soc., December, 1899) have pointed out that considerable variations in the internal distribution of density are possible without invalidating the well-known argument drawn from the phenomenon of the precession of the equinoxes; yet on physical grounds it seems clear that pressure is the principal cause of the increase of density towards the earth's centre. And since this does not vary greatly for moderate changes in the law of density, the principle of continuity shows that the actual law of density within the earth cannot depart very widely from that of Laplace. The above value of the theoretical rigidity of the earth may therefore be taken as essentially accurate, and I think no doubt can remain that the rigidity of our earth as a whole considerably exceeds that of steel. The original conclusions of Kelvin and Darwin are therefore confirmed by the present dynamical considerations based upon the theory of universal gravitation."

In this connection we should remember that the experimental rigidity of steel is 808,000 and of glass 235,000 atmospheres. The calculated rigidity of all the matter within the globe, found by considering not only all the layers, but also the density in each layer, is found to be 1,028,702 atmospheres. Now the average rigidity must be greater than 750,000, because the stiffness of the crust and increase of viscosity downward is neglected in the gravitational method. In fact this method is not applicable to the outermost layers, because the pressure there is much less than the rigidity, and only becomes equal to the rigidity at a depth of something like one tenth of the radius, where the pressure is 320,295 atmospheres.

According to the experiments of Milne and Gray the rigidity of granite is about one sixth that of steel; and as steel has a rigidity of 808,000 atmospheres, that of granite is about 135,000 atmospheres, or a little more than one half that of glass. We may therefore take

the outer layers of our globe to have a rigidity about half that of glass, and assume that at a depth of 0.1 of the radius it becomes nearly 2.5 times as great as it is at the surface. ●

Whether it becomes at a depth of twenty miles less than it is at the surface we cannot tell, but such a decrease is not impossible, perhaps not improbable; because at this depth the molten rock moves in earthquakes, and yet in confinement it must have a very sensible rigidity, though probably not more than half that of granite.

Accordingly, it looks as if the rigidity at the surface is about half that of glass, at a depth of 20 miles about one half that at the surface, and at the depth of 40 miles nearly the same, but increasing below that depth and at 160 miles again equal to that at the surface, and at a depth of 400 miles considerably larger yet, or about 1.4 times that of glass. Increasing below this depth according to the pressure, it becomes at the center over 3 times that of nickel steel used in armor plate. The rigidity of steel is attained at a little over 0.3 of the depth to the center of the earth. If this be the distribution of rigidity in the earth, the curve of rigidity is as follows:

This postulated fall in the rigidity just beneath the crust is probable for several reasons:

1. The temperature increases quite rapidly as we go downward, while the pressure increases proportionately more slowly, so that a depth would be reached at which the matter would become a plastic if not a viscous fluid.
2. The eruption of volcanoes and lava flows on a vaster scale show that a molten layer underlies the crust, and occasionally is forced to the surface.
3. This underlying molten rock moves in world-shaking earthquakes, and frequently is expelled from beneath the sea under the land to form mountain ranges along the coast.
4. We may prove this expulsion of lava by the observed seismic sea waves which indicate a sinking of the sea bottom, and by the simultaneous uplift of mountains and coasts.

From these considerations it follows that the earth is most nearly liquid just beneath the crust, and has the greatest rigidity at the center. As the plastic or quasi-viscous layer beneath the crust is thin, and possessed of considerable rigidity, *it too remains quiescent*

except when set in motion by the dreadful paroxysms of an earthquake.

In tidal and other observations the earth therefore behaves as a solid, and the rigidity of the earth inferred by Kelvin and Darwin is confirmed. Yet a layer of plastic matter or quasi-viscous fluid exists just beneath the crust, and when disturbed by earthquakes gives rise to the development of ridges in the crust called mountains, chiefly by the expulsion of lava from under the sea.

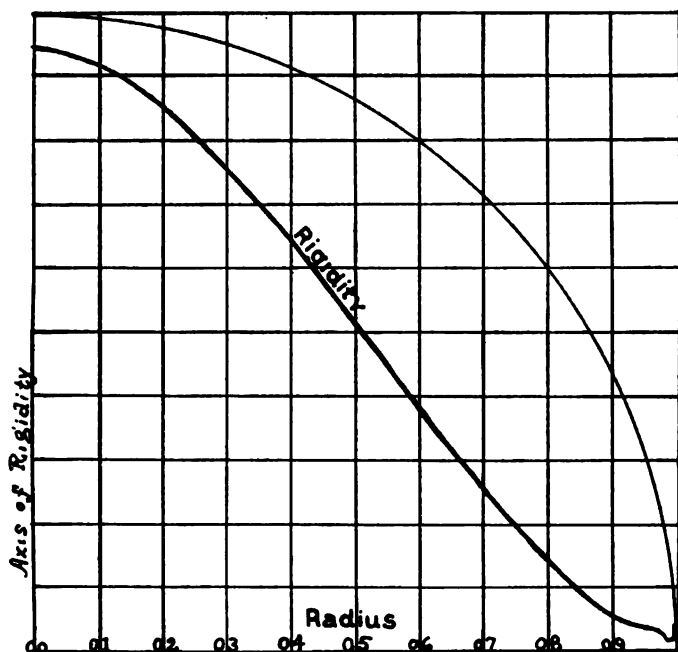


FIG. 2. Curve of Rigidity for the Earth, showing the plastic layer just beneath the crust.

§ 18. *Wiechert's Researches on the Interior Constitution of the Earth and on the Plastic or Viscous Layer which he Infers to Exist Just Beneath the Crust from Oscillations of Long Period Noticed in Seismic Vibrations.*—Professor E. Wiechert, of Göttingen, has devoted much attention to the problem of the constitution of the earth's interior. He long ago reached the conclusion that the great interior nucleus probably is a mass of iron covered with a thick

shell of stony material. In the paper which he recently presented to the International Seismological Association in session at the Hague, September 21–26, 1907, he estimates the depth of the stony layer as 1,500 kilometers, which is nearly one fourth of the earth's radius.

This view that interior of the earth is metallic has been entertained by many eminent physicists, including Lord Rayleigh; but it is beset with many difficulties. We shall here mention three of the principal objections:

1. If this constitution of the earth be admitted, the curve of density will have a sudden break at a depth of about one fourth of the radius; and, as the pressure increases rapidly as we go downward, it seems improbable that the density of the outer layer could remain uniform and then change suddenly at a depth of one fourth of the distance to the center. Such discontinuity in nature seems highly improbable for the density, since there probably is no sensible discontinuity in the laws of pressure and temperature.

2. If the central nucleus is metallic, it follows that the denser elements have separated from the rest of the mass. As the matter has been essentially solid and highly rigid, owing to the pressure, ever since the globe attained anything like its present dimensions, this sinking would not be possible, because the resistance to the motion would be much too great. Thus owing to resistance to motion arising from rigidity we can not admit a separation of the denser from the lighter elements of such a globe. If the metals were all so deep down, it would be hard to account for the veins found in the crust by any kind of eruptive process, since the globe is never fissured to a depth of anything like one fourth of the radius.

3. If in addition to these mechanical objections we recall that deep down the pressure is so great as to cause an interpenetration of all the elements, whatever be the temperature, but especially under the high temperature known to prevail in the interior of the globe, so that no aggregation or crystallization of substances would be possible, and the nucleus would therefore be a magma of all the elements, it becomes inconceivable that the metals could separate from the stony elements by sinking, while the latter floated to the

surface. Even if the globe were a liquid mass of very small viscosity, it is clear that such a separation of the elements could not take place.

Finally it is to be recalled that recent experiments with radium have shown the probable transmutation of some of the metals, as when Sir Wm. Ramsay caused sulphate of copper to be partially degraded into lithium. If this can occur for one or two metallic elements, it may eventually be possible for many and perhaps all of the metals. Our knowledge of these transformations is still in its infancy, and we can not yet ascertain how minerals and metallic veins have arisen; but it is impossible to believe that the material has come up from a pure supply at a depth of 1,500 kilometers. It is much more probable that the metallic elements have been developed by differentiation and transformation from an original magma, and that the whole interior of our planet is still a magma. Differentiation of the elements appears to develop under conditions met with in the crust, but nowhere else.

Accordingly we are obliged to dissent from the constitution of the globe outlined by Professor Wiechert; but in the matter of the existence of a layer of plastic or fluid material just beneath the crust, which he infers from the long seismic vibrations with periods of about eighteen seconds, we are in hearty accord with him. This is definitely proved by the phenomena noticed in earthquakes, as more fully set forth hereafter. It is the expulsion of lava from under the margins of the sea which produces world-shaking earthquakes and the upheaval of mountains along the sea coasts.

§ 19. *On Sir G. H. Darwin's Researches on the Stresses in the Interior of the Earth Due to the Weight of Continents and Mountains.*—We have seen that the earth behaves as a solid at all depths, unless it is in the thin layer just beneath the crust, in which movements take place during earthquakes. The theory of an elastic solid shows that when such a body is stressed the state of stress is completely determined when the amount and direction of the three principal stresses are known. No limit is imposed on these stresses by theory, but in practice nature fixes a limit, beyond which the elasticity breaks down, and the solid either flows or ruptures by breaking.

In the "Nat. Phil.," Vol. I, part II, § 832, Lord Kelvin and Professor Tait remark that

"The precise circumstances under which elastic bodies break have not hitherto been adequately investigated by experiment. It seems certain that rupture cannot take place without difference of stress in different directions. One essential element therefore is the difference between the greatest and least of the three principal stresses. How much the tendency to break is influenced by the amount of the intermediate principal stress is quite unknown. The difference between the greatest and least stresses may however be taken as the most important datum for estimating the tendency to break. This difference has been called by Mr. G. H. Darwin (to whom the investigation of which we speak is due) the 'stress-difference.'"

Stress-difference is a term which when applied to matter within the earth denotes the tendency to flow. For rupture is not possible when the matter is in confinement under such pressure and at high temperature. Now if the earth were homogeneous, as assumed in Darwin's inquiry, the inequalities of surface due to the mountains, plateaus, and continents would give rise to a stress-difference in the underlying layers; and Darwin showed that the stress-difference would increase with the depth, being at the center, for inequalities of the type represented by harmonics of the second order, eight times what it is at the surface.

If the earth were not effectively solid throughout, a flow ought to take place either near the surface or at greater depth; and thus the inequalities of surface would disappear. But the plateaus and mountains do not sink in, and this fact proves that the globe is not fluid, and even that the plastic or viscous layer just beneath the crust is quite stiff. As we have seen that the rigidity increases very rapidly towards the center, we easily see why movement should not occur at great depth, since the rigidity there exceeds that of any known substance, and at the centre is about three times that nickel steel used in armor plate.

In the paper on the "Temperature of the Earth" we have shown from the evidence of stability afforded by geological pinnacles millions of years old, that no movements of deep seated character occur within the earth. This evidence supports the view that the earth is effectively solid, and has behaved as such since the consolidation of the crust.

As the rigidity increases so rapidly towards the center of the earth, flow ought not to take place at those depths; and the absence of any evidence of deep seated movements among the ruins wrought by geological time in turn supports the theory of rigidity depending on the pressure.

Darwin's hypothesis of homogeneity is only a rough approximation to the truth, and Laplace's law would no doubt give a much more exact representation of the density and the resulting stress-difference in the earth. But this suggested change of data would not greatly modify the general conclusions already stated.

§ 20. *The Theory of Isostasy.*—A more important difference might arise from the theory of isostasy, the applicability of which to the earth seems to be becoming better established by recent researches. In this view the crustal inequalities seen at the surface are compensated for by lighter or greater densities beneath, according as the crust is elevated or depressed, so that for a certain thickness of crust equal blocks have equal mass, however unequal the level of the blocks at the surface.

The recent investigations by the U. S. Coast Survey indicate that the depth of complete compensation for the United States and outlying stations is about 71 miles. No doubt a depth of something like this extent would hold true for the entire globe. If this view be admissible, it will follow that all inequalities of the crust cease to be effective at depths greater than 71 miles, and no stress-differences depending on plateaus and mountains would exist in the globe except in the layers just beneath the crust. There would thus be no stresses in the deep interior depending on the weight of continents and mountains.

This theory of isostasy is confirmed by the theory of mountain formation developed in the paper on the "Cause of Earthquakes," which shows clearly that these elevated ridges are underlaid by material lighter than the average rock of the crust. On the one hand, therefore, if stress-differences exist deep down, no movement can take place, owing to rigidity; on the other, if the theory of isostasy be admissible, no stress-differences can exist except in the outer layers of the globe, within 71 miles of the surface.

We conclude therefore that in no case could movements occur

except in the layer just beneath the crust. These superficial movements are called earthquakes, and are caused chiefly by the leakage of the oceans. Observations show that the depth of such disturbances in all cases is less than 40 miles. This accords with the theory of isostasy, and confirms the conclusions drawn from that theory that all surface inequalities are compensated for at but a slight depth.

§ 21. *Uplifts along the Andes show that the mountains are not sinking under their own weight.*—In Professor Sir G. H. Darwin's paper on the stresses in the earth, above cited, he has also considered harmonics of high order, corresponding to the case of a series of parallel mountains and valleys, which thus corrugate a mean level surface with an infinite series of parallel ridges and furrows. Here the stress-difference depends only on the depth below the surface, and is independent of the position of the point considered with respect to ridge and furrow. Taking a series of mountains 13,000 feet (about 4,000 meters) above the valley bottoms, formed of granite of density 2.8, he shows that the maximum stress-difference is 4×10^5 grammes weight per square centimeter (about the tenacity of cast tin). And when the mountain chains are 314 kilometers apart, making the ridges about 78 times wider than they are deep, the maximum stress-difference is reached at a depth of 50 kilometers below the surface, or at a depth of $12\frac{1}{2}$ times the height of the mountains above the valleys. Thus for mountains of the height of our average ocean depth, the maximum tendency to flow would be at a depth of about 31 miles. (Cf. "Nat. Phil.," Vol. I, Part II, § 832.)

If earthquake shocks were due to such flowage the mountains would be gradually reduced in height. Instead of this settling occurring, mountains like the Andes are still rising, as we may infer from the fact that after an earthquake the adjacent sea coast often is elevated and higher than before; while the sinking of the adjacent sea bottom, indicated by the accompanying seismic sea wave, shows that the bed of the sea was undermined by the expulsion of the material pushed under the land and mountains. *This state of fact emphatically contradicts the view that these great seismic disturbances are due to the flowage beneath the crust arising from the*

weight of continents and mountains. Neither the uplift of mountains about the sea coasts, nor the earthquakes occurring in these regions can be explained by flowage beneath the crust, because the movement is positive rather than negative, as required by this theory.

Whilst the investigation of Professor Sir George Darwin therefore does not give us a clue to the observed movements, it is nevertheless very valuable as furnishing an indirect confirmation of the present theory that mountain formation depends on the sea. Observation shows that the movements are positive, and as the theory of flowage indicates that they should be negative, we may infer that whatever be the stress-differences existing beneath the earth's crust, the movements thus produced are insensible compared to those depending on the expulsion of lava from under the sea by world-shaking earthquakes.

III. THE NEW PHYSICAL THEORY OF EARTHQUAKES AND MOUNTAIN FORMATION BASED ON THE SECULAR LEAKAGE OF THE OCEAN BOTTOMS.

§ 22. *On the Plastic and Perhaps Viscous Layers Just Beneath the Earth's Crust.*—We have now examined at length the arguments in regard to the constitution of the earth's interior, and have shown that although as a whole the earth is solid, owing to the pressure to which the matter is subjected, there is a plastic layer just beneath the crust which in earthquakes is made to flow and behave almost as a viscous fluid. In this layer just beneath the crust either the pressure is not great enough to produce entire solidity, with the existing temperature, or else the solid is made to flow by the breaking down of the elasticity under the action of the earthquake forces, which are powerful enough to disturb the whole world.

Although the matter in this substratum appears to have some rigidity, it seems probable that it has not the requisite elasticity to behave as a perfect solid. We know that the layer must be nearly solid, because, if it were not so, there would be a greater tendency of the mountains to subside than actually is observed. The stress-difference in the layers just beneath the crust must be very considerable; and yet this plastic matter is so stiff that it does not flow and allow the mountains and plateaus to sink in.

Now earthquake disturbances are often complex, and consist in horizontal and vertical movements combined. We have seen that in the long run the uplifting tendency predominates, because it is in this way that the mountains and plateaus have arisen. Nevertheless there are numerous cases in which subsidences take place, and these settlements often seem to be somewhat gradual, as if the substratum was slowly yielding and flowing under the stresses to which it is subjected. These gradual subsidences, of the class that was observed by Darwin and Fitzroy at Conception in 1835, seem to afford convincing evidence that the layer beneath the crust is certainly plastic, perhaps viscous.⁴ The yielding of the layer beneath the crust is shown not only in movements noticed in earthquakes, when lava is expelled from under the sea and pushed under the land; but also in the subsidences which the sea trenches experience after earthquakes. These subsidences have folded the rocks seen in mountain ranges now on land; and although most of such subsidence is due to the undermining of the troughs by the expulsion of lava, it seems likely that some very gradual yielding also takes place. The layer under the crust is therefore certainly plastic, when partially undermined, and probably so, independent of the undermining, if it is subjected to great forces, as in world-shaking earthquakes, where mountains are in process of upheaval. If the matter is also viscous, the viscosity must be very high. With the matter imprisoned beneath the earth's crust it is difficult if not impossible to distinguish between plasticity and true viscosity, because, if the fluid is very stiff, it would behave almost as a solid. And the tests heretofore afforded by earthquakes are not decisive. This view of the substratum just beneath the crust is not essentially different from the theory held by Arrhenius with regard to the interior of the earth as a whole. But this layer is the only part of the interior in which movements may be observed, and even here movements would not take place but for the steam developed beneath the crust by the secular leakage of the oceans. It may be that the future study of these movements will some day

⁴We follow Sir George Darwin in "distinguishing viscosity, in which flow is caused by infinitesimal forces, from plasticity in which permanent distortion or flow sets in when the stresses exceed a certain limit." (Letter to Sir A. Geikie, January 9, 1884.)

enable us to decide whether the substratum is plastic only, or truly viscous.

§ 23. *Substratum Everywhere Quiescent Except when Disturbed by Earthquakes.*—The fact the large areas of the earth's surface in such dry countries as Sahara, our Western Plateaus, and the interior of Australia, are quite free from earthquake disturbances, shows what would happen everywhere but for the presence of surface water, and especially the leakage of the crust depending on the sea. The quiescence of the substratum in interior regions remote from the sea shows that under normal conditions this layer is quite inert. It is only set in motion by the vapor of steam which slowly develops stresses in the rocks of the crust and finally brings on earthquakes. It might be plastic enough to yield slightly under sufficiently great forces, but the loading and unloading due to meteorological and geological causes going on in nature are not great enough to have any appreciable effect, as we may infer from the universal quiescence of inland areas, especially in desert countries.

It seems to be true, however, that when the crust is broken and upheaved, in the formation of mountains near the sea coast, some slow yielding takes place beneath. Yet at present any changes of a creeping nature can not be entirely separated from those depending on the expansion and expulsion of lava from under the sea; and we can only feel sure of the inert character of the substratum, except where disturbed by water vapor entering from without. Along the sea coasts the stresses in the crust are constantly changing, and the crust blocks yielding more or less to the stresses acting upon them; it is only when *sudden yielding* occurs that we experience a shock, and the greatest earthquakes are characterized by molten rock adjusting itself beneath the crust. It is probable that much yielding takes place which is exceedingly gradual and produces no disturbances sensible to ordinary observation. In dry regions remote from the sea there are no shocks, and therefore also no gradual yielding of the crust; hence the substratum is inherently and naturally quiescent except when disturbed by external forces.

§ 24. *Mountain Formation in the Sea and on the Land.*—In the paper on the "New Theory of Earthquakes and Mountain Formation," we have cited certain cases of mountain formation now going



FIG. 3. Relief Map of North America. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) This map illustrates beautifully the recession of the sea since the formation of the Rocky Mountains, which were at one time the eastern border of the Pacific Ocean.

on in the depths of the sea, and directly connected with mountain systems spread out on the land. Thus we have shown that the Aleutian Islands are a branch or part of the Rocky Mountains still remaining in the depths of the sea. As this part of the chain is now being uplifted by the ocean, we get a very clear conception of how the whole Rocky Mountain system was formed. We are fortunate therefore to find a part of a great mountain chain still unfinished, with one end under water and the main body of the system high and dry along the edge of the continent.

Now no one believes¹ that mountain formation takes place far inland, because the mountains generally follow the coast, and moreover at present the process is found to be most active *in the sea*, as in the region of the Aleutian Islands and the Antandes. This geographical distribution of mountain-making is therefore a most powerful argument for the new theory. Moreover it is generally recognized that the Rocky Mountains in the United States are a good deal older than the Andes in South America; and as the relative ages bear some relation to the distances from the sea, the mountains on land give the same indication as those still in the depths of the sea. The recession of the sea goes on at very unequal rates in different parts of the world, yet the present positions of the mountains show that the older mountains are generally remote from the ocean. The present theory is therefore confirmed by the lay of the older as well as of the younger mountain systems; and by the situation of the mountains on land as well as of those now being formed in the depths of the sea. All the mountain phenomena of the globe are thus shown to be consistent. But as direct observation of mountain formation witnessed with our own eyes is the most convincing of all evidence, it is fortunate that we are able to cite numerous cases of mountain ranges now developing in the sea. By the study of the sinking going on where trenches are developing, we see how the wrinkles and valleys were produced in mountain systems now at a considerable distance from the ocean. Since the sea recedes from the mountains in the course of geological ages, it follows that more and more land is constantly rising above the water,

¹ Compare § 42 of this paper, where Leconte's views are quoted at length. He held that mountain ranges are formed on lines of thick sediment along the shores of continents.

and the continents growing larger. The mountains are formed by earthquakes, and earthquakes are due to the sea, which thus makes more and more land for the development of the higher forms of life upon the globe.



FIG. 4. Relief Map of the United States. (From Frye's Complete Geog-
especially how the great plateau west of the Rocky Mountains has been

§ 25. *The Origin of Faults in the Earth's Crust.*—It has long been recognized that faults in the earth's crust are often displaced by earthquakes. Now earthquakes are mainly submarine or follow the borders of the continents. Here the mountain ranges have de-



raphy, by permission of Ginn & Co., Publishers.) The reader should notice crumpled in the uplift from the sea, which has receded westward 1,000 miles.

veloped or are now developing, and in general the faults run along the sea coasts and into the sea, where mountain formation is in progress. Thus it is clear that faults arise from the stresses and movements of the crust produced by earthquakes and mountain formation, and therefore from the secular leakage of the ocean bottoms.

Sometimes the faults move but little, at other times they give rise to conspicuous changes of level; and where vast down-throws or uplifts have occurred certain types of mountains arise from normal faulting. The more horizontal movements of faults arise mainly in the trenches along the sea coasts, which produce the folding seen in mountain chains. The vertical movements are more general, and are especially conspicuous in elevated plateaus, like those of our western states.

In his "Report on the Geology of the High Plateaus of Utah," Washington, 1880, Major Dutton gives a description of some of the most magnificent faults in the world. On page 45 he indicates the dependence of these faults on the ancient shore line of the Eocene lake, thus:

"It yet remains to speak of another interesting relation of the later system of faults. They have throughout preserved a remarkable and persistent parallelism to the old shore line of the Eocene lake, following the broader features of its trend in a striking manner. The cause of this relation is to me quite inexplicable, so much so, that I am utterly at a loss to think of any subsidiary facts which may be mentioned in connection with it and which can throw light upon it."

What puzzled Major Dutton most was the raising of the area of the lake; but as the whole region was uplifted by the sea in later times this phenomenon was in no way remarkable. The rocks in such disturbed regions have been broken and folded into a series of troughs and arches or thrown into domes and basins, and probably no two adjacent areas retained their relative levels throughout. His observation, however, confirms the present theory that faulting is generally parallel to the ancient sea shore, and therefore produced originally by the oceans.

The conspicuous character of the vertical movement of the crust blocks in the region of the Great Basin led several American geologists to suggest that vertical forces had operated in the uplift of

these plateaus. As the whole region has been raised from the sea by the injection of the land with lava pushed under the crust from beneath the sea, it is evident that the crust blocks ought to be displaced unequally in different places, and hence the various types of faulting observed.

It should be remarked, however, that in the elevation of a plateau a mile high, only a layer of lava a mile deep needs to be injected. If three miles high, the layer would have to be three miles thick; but even this maximum height is only about one seventh of the thickness of the crust; and hence eruptions would not usually occur in these uplifts. The plateaus are all of small height compared to the thickness of the earth's crust, beneath which the movement of molten rock takes place.

If some faults should thus be widely opened, lava flows of vast extent, like those in Utah and Oregon, might be expected to occur. We cannot give the details of the cracks which produced these gigantic outflows, but it is evident that they depended on the opening of immense faults. Now the faults are produced and moved by earthquakes, and earthquakes are due to the leakage of the oceans. It follows therefore that the most immense lava flows ought to take place near the sea; and this seems to be true both in North America and in Asia, where the outflow in the plateau of Deccan has always excited the wonder of the naturalist.

That all the faults of the earth's crust depend on the sea and are produced by world-shaking earthquakes, is clearly indicated by the geographical distribution of these cracks in the crust. If any other cause, such as the secular cooling of the globe, were at work, we should find a relatively greater predominance of faults far inland, which is contrary to observation, especially in dry countries.

It is remarkable that geologists have referred so many phenomena to faulting, but have made little or no attempt to explain faulting itself. In the present theory referring the origin of faults to the expulsion of lava from under the sea we have for the first time a satisfactory and consistent view of these phenomena. Faults evidently arise mainly from the motion of lava in earthquakes, by which the overlying rocks of the crust are broken, and often displaced along the line of fracture.

When the crust is thus rent into blocks, some of them are reduced to small size, and eventually raised up, as in the vertical walls of granite now seen in Smyth's channel, southern Chile, the Straits of Magellan, Yosemite Valley, California, and the fiords of Norway. These precipitous walls of granite could be pushed up only by vertical forces, in earthquakes. It is noticeable that no such isolated masses are found towering up in the plains of Kansas, the desert of Sahara, and other inland regions far from the oceans. The origin of faults and fault movements must therefore be sought in the leakage of the oceans and in the resulting relief, which takes place in the sea bottoms and along the borders of the continents.

§ 26. *On the Uplift of the Great Plateaus of the World and on the Gradual Elevation of the Continents.*—For reasons already amply set forth in § 7, the process involved in the formation of the Andes is clear and beyond dispute. Now it happens that the Andean plateaus, such as those of Quito, Caxamarca, Cuzco and Titicaca, are generally included between the eastern and western ranges of the Andes, and were evidently uplifted by the same forces which formed the mountains themselves. Accordingly it is clear that a plateau such as that of Titicaca was therefore uplifted by the expulsion of lava from under the sea.

If now we pass from the Andes to the Himalayas, we shall find that in like manner those great mountains of Asia were uplifted principally by the Indian Ocean. The plateau of Thibet in the Himalayas of Asia corresponds exactly with that of Titicaca in the Andes of South America; and as the latter was formed with the Andes, so also the plateau of Tibet was formed with the Himalayas. This seems absolutely clear and incontrovertible. And a similar mode of development must be ascribed to the table lands to the east and west of Tibet, so that the principal plateaus of Asia, Tibet and Iran, are clearly the work of the sea.

The highest part of these plateaus is Tibet, with an average elevation of about 15,000 feet, and a width of about 500 miles at the highest part. At the middle it is somewhat wider, and to the west it narrows into Little Tibet, less than half the width of Tibet proper. It is evident that great Tibet was uplifted chiefly by movements from the direction of the bay of Bengal; this is shown by the lay of

the mountain chains south of Tibet, and by the great earthquake belt still persisting in the valleys of the Ganges and Brahmaputra.

In the case of North America the plateaus are broader and correspondingly lower than those of South America and Asia. But if the sea gave rise to the uplifts connected with the Andes and Himalayas, can anyone doubt that the plateaus of North America are due to the same cause? The *total volume* of the North American



FIG. 5. Relief Map of Asia. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The mountains along the east coast illustrate the successive stages in the recession of the Pacific Ocean. At some future time the border of the continent will extend to the string of islands running from Kamchatka to the Philippines, the shallow seas of Japan and China becoming inland valleys.

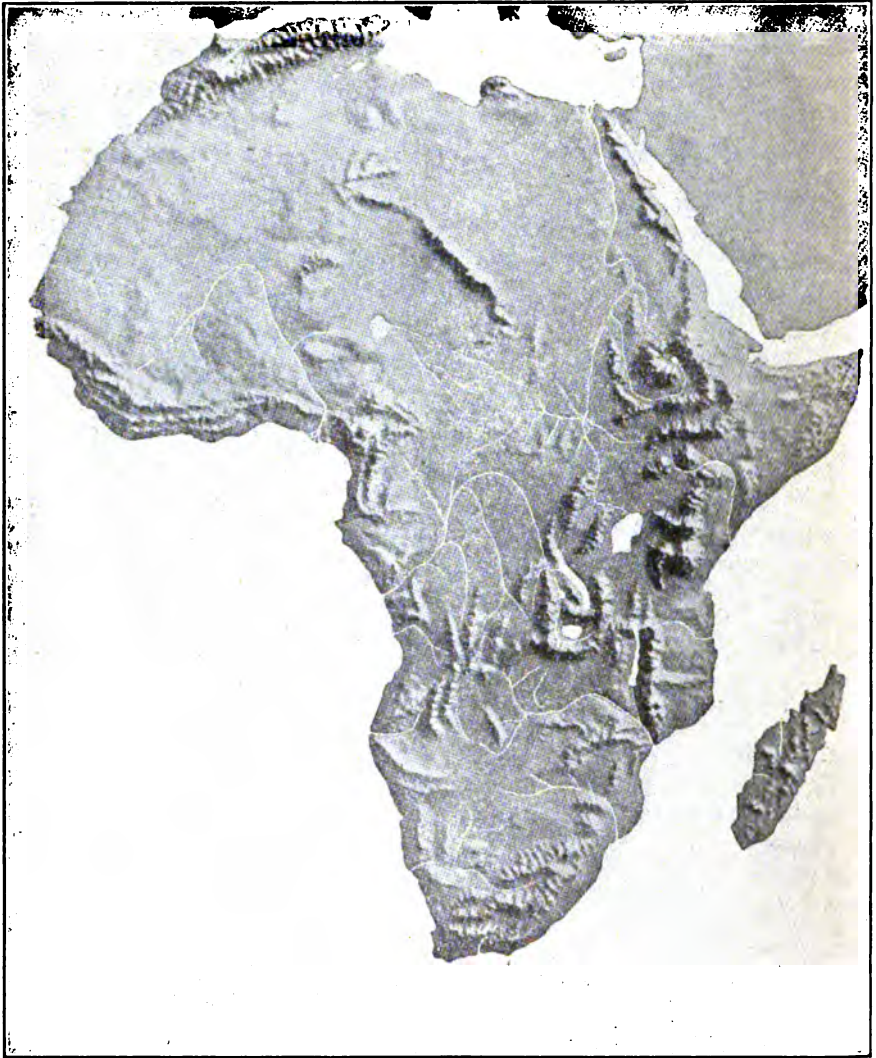


FIG. 6. Relief Map of Africa. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The reader should notice how the highest mountains along the east coast face the Indian Ocean, which is a continuation of the Pacific.

plateau is comparable with that in Asia, and it is easy to see how the relief of the Pacific on our side may have taken the form of a table-land of greater width but smaller height. The numerous parallel mountain chains west of the Rocky Mountains show the nature of the mighty forces at work, and prove that this uplift was the work of the Pacific Ocean.

§ 27. *The forces which have raised the mountains and plateaus of the globe are identical with those which have raised the continents above the sea, and all these forces depend on the leakage of the oceans.*—The geological evidence of the slow operation of the forces which have uplifted the plateaus and mountains shows the immeasurable ages during which they have been at work. Sometimes large portions of a continent have risen for a time, and again slowly subsided, and thus have arisen the phenomena noted in the sedimentary rocks studied in geology. These gentle movements often are without violent earthquake shocks, because the yielding is very gradual, and the crust is slowly raised up and down without breaking. It is only where the expulsion of lava from under the sea is rapid and violent that breaking develops at such rate as to form mountain chains and plateaus. The uplift of a plateau also requires a large amount of material. Where the process is gentle and gradual a whole continent may be slowly uplifted, and this process evidently has raised the low broad plains above the water. *The cause of epeirogenic and of orogenic movements is everywhere one and the same.* The movements take different forms according to the suddenness with which the forces act; but both depend on the leakage of the oceans, and not at all on the secular cooling of the globe, the effect of which is insensible.¹

¹ Since this was finished the writer has carefully recalculated the shrinkage of the earth's radius in 2,000 years, and finds that it can not exceed 1.5 inches. This takes no account of the increase of the interior heat of our globe due to radio-activity. If this latter effect were taken into account probably there would be no shrinkage whatever. Quite independently of these effects, however, there is an actual expansion of the globe due to the leakage of the oceans.

In the same way it is found, by the application of Fourier's theory of heat to the cooling at the surface, that the total shrinkage in the *length* of a continent such as North or South America, assumed to be equal to the terrestrial radius in length, is less than 1.5 inches. This again takes no

Such an inference seems justified by the study of the mountains and plateaus of the world, and also by the movement of the strand line which Professor Suess has so carefully traced in every country. Almost everywhere the level of the sea has been lowered in recent geological time.

During his travels in South America, Darwin recorded many observations to show that Patagonia and the whole end of the continent south of the La Plata had been recently elevated above the sea; and he mentions a channel in the Andes quite a distance north of the Straits of Magellan which gave evidence of the former passage of the sea through it. In view of these well-established facts, can any one doubt that the Straits of Magellan will eventually become dry and Tierra del Fuego be added to Patagonia? This whole region shows vast walls of rock towering vertically thousands of feet above the sea; evidently they were uplifted by earthquake forces from beneath, sometimes working quietly, and again spasmodically.

As surely as Calabria in Italy has been uplifted from the Mediterranean, by that sea, just so surely has the southern end of South America been raised up by the southern ocean. And if an end of a continent can be upraised, obviously whole continents can be uplifted. Accordingly in the leakage of the oceans and the relief taking place under the land which bounds them we have the true cause of continent-making.

Some original inequalities of surface may have existed after the detachment of the moon from the consolidating globe, but these have since been enormously increased by the effects resulting from the leakage of the oceans. As the earth gets older, the lithosphere becomes more diversified, and the face of the earth more and more wrinkled.

The situation of the great plateaus of the world facing the largest oceans gives a clear indication of the nature of the forces at work account of radium, the effect of which would be to diminish this calculated shrinkage, or do away with it entirely. By such comparisons as these, placed along side of the large horizontal and vertical movements noticed in earthquakes near the sea, which sometimes amount to from 30 to 50 feet at a single disturbance, we see the utter untenability of the old theories heretofore current in works on geology and the related sciences. Note added July 28, 1908.



FIG. 7. Relief Map of Australia. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The reader should notice how the largest mountains along the east coast face the Pacific Ocean.



FIG. 8. Relief Map of Europe. (From Frye's Complete Geography, by permission of Ginn and Co., Publishers.) The reader should notice how the principal mountain chains face the Mediterranean and the Atlantic. There is a trough in the sea bottom off the Scandinavian coast to which Professor Schiaparelli has called attention.

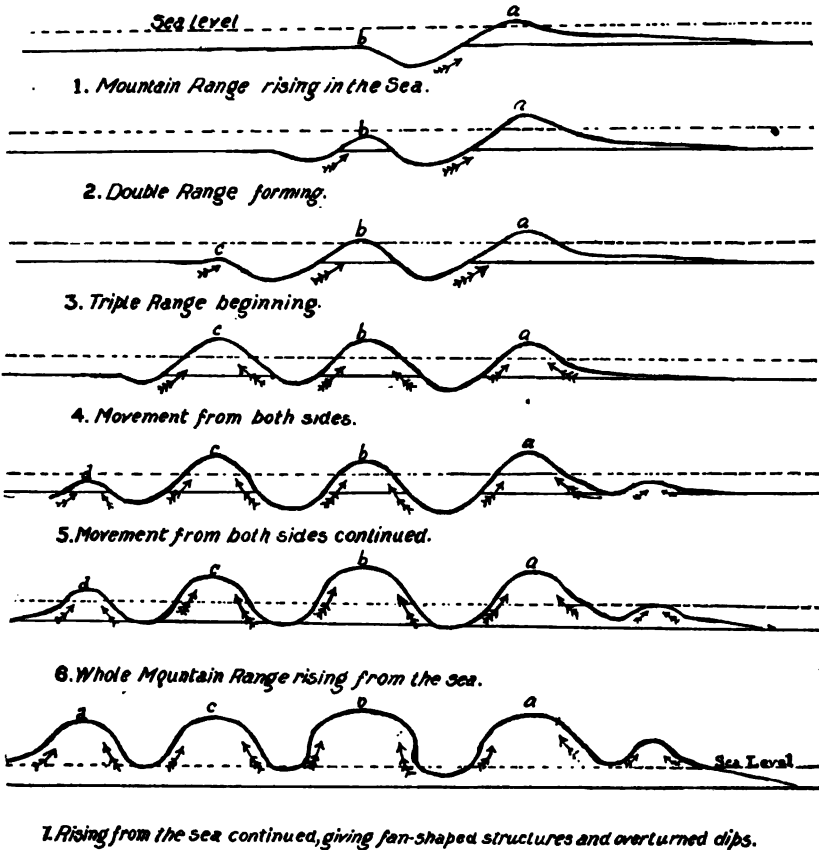
The accompanying figures exhibit: (1) A general section of the Alps from Zürich to Lake Como (Heim and Prestwich), and (2) a section on a larger scale of a portion of the central Alps (from *Heim's Gebirgsbildung*) with fan-shaped folds and inversion of strata on the two sides. It can hardly be assumed that these illustrations are extremely accurate, but no doubt they are free from large errors in exhibiting the general character of the folding, which gives here and there fan-shaped structures with overturned dips at the sides.

Now the explanation of such structures is the most difficult problem heretofore presented to the geologist. They exhibit conspicuous lateral and vertical movements which cannot well be accounted for by the contraction theory. A shortening of about 74 miles (Heim) in the folding, which has amounted to 50 per cent. of the whole span of crust (Leconte), can not be accounted for, on the old theory, without assuming that the crust is loose from the globe, so that a vast amount of slack could be brought forward and concentrated in the folds at one point, in the Swiss Alps. This is clearly unthinkable. On the other hand, the cone of matter underlying the Alps with vertex at the center of the earth could not be sufficiently condensed to give the required slack in the overlying crust without increasing the density of the cone by 50 per cent., which could easily be detected by geodetic observations, owing to the resulting deviations of the plumb line. Accordingly we may feel sure that the matter under the Alps not only is not denser than the average, but actually lighter, by an appreciable amount. The crumpling of the Alps cannot therefore be due to condensation beneath these mountains.

How then did the folding arise?

If we cut a section across the Aleutian Islands perpendicular to the chain and the parallel trench lying to the south, we shall have a figure something like that shown in figure 1 of the following plate. Now in the paper on the "Cause of Earthquakes" (§ 16) we have shown how the undermining of the sea bottom sinks the trough down deeper and deeper, and as the expulsion of lava continues it eventually becomes easier to fold up the side of the trough towards the ocean (at *b*) and make another range of mountains parallel to the first. And there is nothing to prevent the process from being re-

peated several times. When several successive ranges of mountains are thus developed in the process of expulsion under the margin of the sea, it is easy to see that the central range may finally be driven upward and flared out at the top exactly as in the Alps. Thus all this movement occurs in the sea, and eventually the range becomes like that now seen in Switzerland, as depicted by Heim, of Zürich.



1. Rising from the sea continued, giving fan-shaped structures and overturned dips.

FIG. 11. Illustration of Formation of Complex Range, such as the Swiss Alps. The bending of the crust has caused it to pull apart at the top and bottom of the folds, where it is largely covered by sedimentary deposits and filled by molten rock from beneath, so that the breaks do not show at the surface, unless erosion has laid bare parts of the underlying structure. In these figures the thickness of the crust is less than half the width of the folds; and for clearness the depth of the sea is exaggerated.

As the movement continues the central range rises upwards, while its flanks sink down on either side, and thus the fan-shaped structure develops, 'so as to give overturned dip and inversion of strata once deposited horizontally in the bed of the sea.

This is a perfectly simple and direct explanation of one of the most mysterious phenomena heretofore encountered by naturalists.

The new theory of mountain formation is proved to represent a real law of nature by phenomena now witnessed in the Aleutian Islands, Japan and elsewhere. The fact that it perfectly accounts for the perplexing phenomena seen in the Swiss Alps, shows that they too were formerly under the sea, and were uplifted by the same force now at work in the Aleutian Islands and the Antandes.

Accordingly it is not remarkable that Professor Suess should, without knowledge of the *true cause*, describe the uplift of the Alps from the sea in words which are almost prophetic ("Face of the Earth," Vol. II, p. 552) :

"As a result of *tangential thrusts*, the sediments of this Sea (Mediterranean) were folded together and driven upward as a great mountain range, and the Alps have therefore been described as a compressed sea."

Without overestimating the significance of this result, it seems clear that neither parallel ranges nor fan-shaped structures with inverted dips will hereafter present any further difficulty to the geologist. Now that the true laws of such phenomena are known, it will be exceedingly interesting to work out the details of all the great mountain systems with which the earth is adorned.

§ 29. *All Complex Folding now seen in Mountain Ranges Originated in the Sea.*—It is scarcely necessary to add that all the complex folds now seen in mountain ranges were produced in the sea by the repetition of trenches dug out by earthquakes. The folds were frequently broken apart at both top and bottom, by the earthquake movements, and thus the folded crust is not shortened by anything like so much as has been supposed. Moreover where the fan-shaped structures and overturned dips appear, the two sides were never joined together by an arch above, as represented in the above figures by Heim, but were quite separated before the range arose to any considerable height. Accordingly it follows that erosion has not worn off anything like so much of the top of the range as

the theory of a rounded arch would require. Thus we may not only explain the folds of the Alps, but also recognize that the folds both above and below were less extensive than was formerly supposed; and this greatly simplifies the labor of the geologist in restoring the former structure of mountain chains as they appeared before they were greatly eroded.

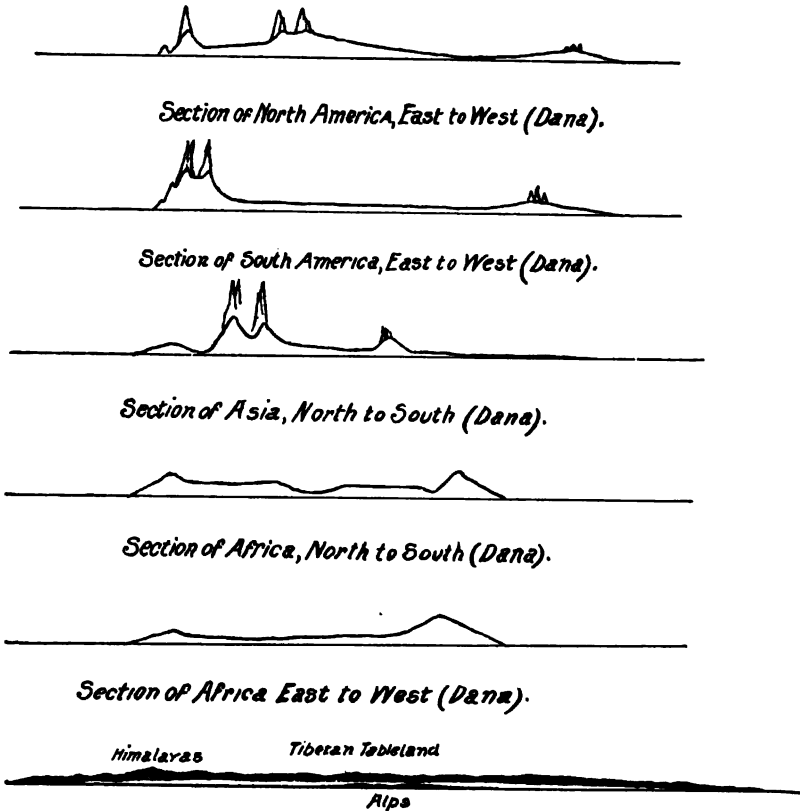


FIG. 12. Sections of the Continents, and of the Alps and Himalaya on the same Scale. (Gen. Strachey.)

The process of undermining the sea bottom in the expulsion of lava arising from the leakage of the ocean, has given rise to all the important folds of the earth's crust. Thus arose all the complicated folds in the Alps, Andes, Alleghenies and other mountain ranges. And wherever we see these folds sea trenches once existed, and the

crust was pushed hither and thither by earthquakes, raising ridges and undermining the troughs, till the rocks were crumpled and folded as we find them to-day. *The simplicity of this cause, and the easy way in which we pass from the living troughs now being dug out in the sea to fossil troughs long since dead and now far inland give a genuine paleontological interest to the science of mountain formation.* What has long been mysterious and nearly inexplicable is now as clear as any theorem in geometry.

§ 30. *Application of the New Theory to the Allegheny Mountains.*—The Allegheny Mountains in Pennsylvania and Virginia are very remarkable for the great extent of the folds, and it seems worth while to dwell a moment on the mode by which these folds were produced. We have seen that they all arose in the sea, and by a repetition of the earthquake process of digging out trenches along the ancient shore line. As we shall see in Part V, § 41 of this paper, Professor James Hall so long ago as 1857 announced to the American Association in session in Montreal that the enormous thickness of the formations along the Appalachian Chain in the United States was due to the prolonged accumulation of sediments over a sinking sea bottom, at the margin of the continent, where the marine currents allowed the material to deposit.

Obviously if sea trenches were dug out by earthquakes they would become the basins for the accumulation of a vast amount of detritus. And when several trenches were successively dug out in the sea bottom by earthquakes depending on the Atlantic, would not the resulting folds give us the Allegheny, Tuscarora and Blue Ridge Mountains of Pennsylvania and Virginia? The famous Shenandoah Valley in Virginia is nothing but an ancient sea trough; and Pennsylvania has many such valleys originally formed in the depths of the sea. This is clearly indicated by the beautiful parallelism of the mountain ranges.

It is noticeable that the sea trench south of the Aleutian Islands is remarkably straight, and one may easily predict that the ranges hereafter to be formed in the North Pacific Ocean will be remarkably parallel like those now seen in Virginia and Pennsylvania. Under the circumstances can any one doubt that the sea was once very deep near where the Blue Ridge stands to-day?

Excluding from consideration the crystalline belt on the east, Claypole estimated the shortening of the Appalachians in Pennsylvania at 46 miles. In the same way McConnell estimated that of the Laramide range in British America at 25 miles, and Leconte that of the Coast Range in California at from 9 to 12 miles. Corresponding estimates have been made for many other mountain ranges; but, for reasons already given in dealing with the origin of the Swiss Alps, § 28, these estimates are too large. The crust was broken apart at both top and bottom when the ranges were in the sea, and the folds heretofore assumed to be complete were never really so. Consequently no slack in the earth's crust is required to explain these folds; it was never loose from the globe and never moved horizontally, except when forced by earthquake movements proceeding from the underlying trenches in the sea bottom.

The undermining and folding of the crust has given the Appalachian Mountains in many places the aspect of a series of immense billows, running parallel, as if swept in by a vast disturbance of the sea. But not even seismic sea waves of the most imposing magnitude could approach the size of these gigantic folds, the origin of which heretofore has been so mysterious. The finding of a simple and natural explanation of *these great billows of the land* will be scarcely less interesting than the discovery of the cause of seismic sea waves. Both depend on earthquakes, though in very different ways. The land billows are cumulative products of an infinite series of seismic disturbances along the margin of the sea; the seismic waves are small in comparison, and result from a single disturbance of the sea bottom, made in process of shaping the vast billows of the land, which in all generations have appealed to the imagination of the painter, poet, and student of nature.

§ 31. *Analogy Between the Uplift of the Islands of Japan by the Movement from the Tuscarora Deep and of the Plateau of Tibet from the Indian Ocean.*—The uplift of the Islands of Japan now going on by the expulsions of lava from beneath the Tuscarora Deep is proved by the terrible earthquakes and seismic sea waves afflicting that region, as well as by the historical fact that the east coast of Japan is known to be rising from the sea. Perhaps in general the movement is slow and insensible, but occasionally earthquakes

have produced large disturbances of the level. The nature of earthquake movement in expelling lava from under the sea is too well known to leave any doubt as to what is going on in Japan. And the theory is confirmed by the fact that if Nipon and Yezo were dug off and thrown into the Tuscarora Deep they would about fill up that profound abyss and leave the sea of average depth.

Now there is a certain analogy between the uplift of these Japanese Islands, which are considerable areas, by the Pacific, and of the Plateau of Tibet by the Indian and Pacific oceans combined. Undoubtedly the valleys of the Indus, Ganges and Brahmaputra are the relics of ancient sea troughs which largely produced the Himalayas and the great plateau of Tibet. How much these troughs have been modified in later geological times we cannot estimate; but even now enough remains to tell the true story of Himalayan development. This is also indicated by the preservation of the earthquake belt south of the Himalayas. The meaning of these valleys and earthquake belts admits of no possible doubt. Just as the whole island of Nipon is being raised by movements from the Tuscarora Deep, so the whole of the Plateau of Tibet was once raised by an Indian Deep, of which these valleys are the remains.

In the same way the Valley of the Po is the remains of the sea valley which was most influential in uplifting the Swiss Alps. But in the case of the Alps, Geikie has shown that there was also a sea on the north, which has now quite disappeared, though traces of its former existence still remain.

§ 32. *The Origin of Volcanoes and the Conditions of their Maximum Development.*—It appears from the line of proof developed in this theory that volcanoes may break forth in any region near the sea where there are severe earthquake disturbances, by which the crust of the globe is sufficiently cracked to afford a vent for the steam imprisoned beneath. Now such vents are greatly facilitated in a chain such as the Aleutian Islands, in which the crumpling is extreme, and the expulsion of lava from beneath the sea rapid and violent. The crumpling breaks the crust along many lines, and as the earthquakes due to the expulsion of lava are both frequent and terrible, the chance of steam breaking through to the surface

is much greater than in regions less wrinkled and less afflicted by earthquakes. The crust in the Andes was once folded by the sea in the same way as that in the Aleutian islands, and from this circumstance arises the violence of the volcanic outbreaks noticed all along the west coast of South America. From the great similarity of the volcanic phenomena in the Andes and in the Aleutian Islands, and its enormous prominence in both ranges, it seems obvious that we have here the conditions for its maximum development.

Charles Darwin believed that volcanoes usually break out in regions of elevation. No doubt this is true, for mountain ranges are the most conspicuous of rising areas. And according to this theory the tendency to rupture the crust is a maximum, when the ranges are being both folded and raised from the sea. Thus while some volcanoes may break out in less fractured regions of the earth's crust, the greatest volcanic activity develops where mountains are being formed in the sea, as in the Aleutian Islands. This view also enables us to understand why many volcanoes in the Andes are now extinct, though they were formerly active for immense periods of time, as we know from the thick deposits of volcanic debris and the immense height of the cones built up of lava, ashes and cinders.

IV. COMPARISON OF THE NEW PHYSICAL THEORY OF MOUNTAIN FORMATION DEPENDING ON THE LEAKAGE OF THE OCEANS WITH THE THEORY OF SECULAR COOLING AND CONTRACTION HERETOFORE HELD BY MEN OF SCIENCE.

§ 33. *General Remarks on the Method of Comparison Adopted.*—

The new physical theory of mountain formation depending on the leakage of the oceans outlined in the three memoirs recently published by the American Philosophical Society and somewhat more fully developed in the present paper might seem incomplete if we failed to compare the new theory with the theory of secular cooling and contraction of the globe heretofore held by men of science generally. On several grounds an examination of the older theory can hardly fail to be instructive. And if this comparison of the older theory with that now adopted shall be the means of har-

monizing in any considerable degree the divergent views heretofore prevailing, and of showing *that there is no important geological phenomenon which the new theory does not explain in a more simple and direct manner than the old theory*, such a comparison will no doubt seem quite justifiable. For it is highly desirable to establish the adequacy of the new theory to explain the *geological* as well as the *physical* phenomena noticed at the surface of the earth.

In making this comparison it is necessary to bear in mind that the geological data on many points are still very incomplete, and therefore we should expect agreement with the body of phenomena rather than with the details, about which much uncertainty still exists. Owing to the incompleteness of our knowledge of the mode of origin of the great mountain chains of the globe, the best plan of procedure seems to be: First, to give an exposition of the views of previous writers in regard to the individual great mountain systems; second, to add a résumé of the views of certain great geologists on mountain formation in general. Obviously such condensation of the views of others should wherever possible be given in their own words.

As this subject is extensive and widely scattered in a variety of publications, we must content ourselves with selecting those citations which seem of most interest, without in any way claiming to exhaust the subject. Indeed it may well be that some discussions of value will be entirely overlooked, but, as the theories have been but very little changed for many years, it is hoped that the following citations will be found adequate to give an intelligent grasp of the views heretofore accepted by the leading authorities. If there be those who doubt the propriety of including lengthy quotations from well-known authors, I must plead in extension of the course here adopted, that this memoir is intended for others besides geologists, and that all who are interested in the physics of the earth, whether they be mathematicians, astronomers, physicists, seismologists, geologists, or even chemists and biologists, are entitled to have a clear summary of the principal theories heretofore accepted in regard to the development of our globe. In dealing with a subject of such universal interest to all men of science, any reasonable condensation of the previous theories may be considered admissible, and one

may have no hesitation in invoking the aid of many authors. If the establishment of a great law of nature may be thus facilitated, surely no one will doubt that the space utilized was devoted to a most useful purpose. The extreme specialization characteristic of the science of our day makes such summaries both useful and necessary for the intelligent study of great problems; and if more effort were made in this direction it might contribute materially to the progress of scientific research.

(A) ACCOUNTS OF PARTICULAR MOUNTAIN SYSTEMS, AND THEIR
SUPPOSED MODE OF DEVELOPMENT.

§ 34. *The Andes*.—We shall begin with the Andes of South America, because this is one of the largest, simplest and most typical of mountain systems; and if a theory will not explain the Cordilleras, we may despair of its explaining the more complicated mountains of the globe. The reader should carefully bear in mind not only what the author in question says from his own point of view, but also how the facts he mentions accord with the new theory developed in this paper.

In the *Encyclopedia Britannica*, ninth edition, under the article "Andes," we find the following lucid exposition of Andean development. It is not signed, but is supposed to have passed under the review of Sir Archibald Geikie.

"The formation of the Andes is due to several causes operating at distinct intervals of time. They consist mainly of stratified material which has been more or less altered. This material was deposited at the bottom of a sea, so that at some former time the highest portions were submerged, probably in consequence to a certain extent, of subsidence of the sea bottom. Since the latest deposits there has been upheaval and denudation. The range, then, has resulted from the accumulation of sediment on a subsiding area; from the subsequent upheaval of such deposits, which have been increased in height by the ejection of volcanic products; and from the operation of denuding agents.

"As far as our present knowledge goes, it appears to be probable that the Andes mark an area on which sedimentary deposits have been accumulated to a greater thickness than on any other portion of South America. It is further demonstrable that these deposits belong to several geological periods, the elevation having occurred at different periods, while their axes extend in different directions. Hence it is a complex range of mountains formed by the combination of several distinct systems of ridges. The width of the

range varies from about 60 to 300 or more miles, but, as compared with other mountains, the Andes are for the most part narrow relatively to their height. Where their special features are most characteristically developed, they consist of a massive embankment-like foundation, rising with a rapid slope from the low country on either side, and having its margins surmounted by lofty ridges of ragged or dome-like summits. These Cordilleras, as they are usually termed, flank longitudinal valleys, or plain-like depressions which form the highest levels of the central portion of the gigantic embankment, and which vary in width from twenty to sixty miles. At intervals the longitudinal depression is broken up, either by ridges connecting the Cordilleras, or by lofty plateau-like uplands. In several cases these transverse ridges and belts of high ground form the main watershed of the country. They are rarely cut across by the river systems, whereas both the marginal Cordilleras are intersected at numerous points, and more especially by the rivers draining the eastern slope of the country. In no case do these eastern rivers originate to the west of the western Cordilleras. A few of the central valleys, or plain-like depressions, have no connection either with the western or eastern river system. Roughly speaking the height of the central plains or valleys is from 6000 to 11,000 feet above the sea; of the passes and knots, from 10,000 to 15,000 feet; and of the highest peaks, from 18,000 to 23,290 feet—the last being the altitude of Aconcagua in Chili, which is generally considered to be the highest peak in America. Judging from these estimates, we may regard the bulk of the Andes as somewhere about that of a mass 4400 miles long, 100 miles wide, and 13,000 feet high, which is equivalent to 5,349,801,600,000,000 cubic feet. On this basis we find that the Mississippi would carry down an equivalent mass of matter in 785,000 years. The rate of denudation in certain river basins varies from one foot in 700 years to one foot in 12,000 years. Assuming that similar rates would apply to the Andes, they would be denuded away in from 9 to 156 million years. In all probability, much less than 9 million would suffice. On the other hand the Andes would be swept away in 135,000 years, supposing the denuding powers of the globe were concentrated on them alone. From the above data, and assuming the average specific gravity of the matter forming the Andes to be 2.5, the weight of the portion above the sea may be estimated at 368,951,834,482,750 tons, giving an average of about 1,000 tons on each square foot at the level of the sea. Under Aconcagua the pressure would be about 1,780 tons per foot at the same level, provided, of course, it were not, as it no doubt is, more or less modified by lateral pressure. These figures afford some, though at best a vague, conception of the mighty grandeur of this range of mountains, and of the scope there is for the exertion of enormous pressure. How vast then, must be those forces which have counteracted such pressures, and upheaved the ocean-spread sediments of the continents, until the Andes, that

‘giant of the Western Star,
Looks from his throne of clouds
O’er half the world!’

But, however vast the Andes may seem to us, it should be remembered that they form but an insignificant portion of the globe itself. Aconcagua is about $1/2,000$ of the earth's diameter, which is relatively not more than a pimple $1/30$ of an inch high on the skin of a tall man." (Ency. Brit., Vol. II, pp. 15-16.)

The account here given of how the Andes were formed seems exceedingly instructive. In the sea troughs formerly existing between the ocean and the eastern range, which was the first thrown up, we have a complete explanation of the extraordinary depth of sedimentation; for in such trenches adjacent to a new range the rate of sedimentation would be a maximum. The subsequent uplifting of the western side of the sea troughs, with the vast lateral folding and compression necessarily accompanying this movement, accounts for the plateaus, valleys and general structure of the Andes, as well as for the violent volcanic outbreaks, which are said to greatly predominate in the range nearest the sea, from which the expulsion of lava giving rise to this mighty Cordillera proceeded. The vastness and height of the Andes and the terrific forces operating to erect this gigantic wall along the shore of the continent is a true measure of the secular leakage of the Pacific Ocean, and of the automatic relief it finds by folding the earth's crust along the border, in the countless successive expulsions of lava from beneath the bed of the sea. It is needless to point out how perfectly the new theory explains the persistence of the earthquake belt along the western shore of South America, and of the seismic sea waves by which that region is so often afflicted. It is obvious that the forces which uplifted the mountain also carried up the plateaus enclosed between the various ranges.

§ 35. *The Himalayas*.—The following luminous account of the Himalayas by the late Lieutenant General Sir Richard Strachey, *Encyclopædia Britannica*, article "Himalayas," is of extreme interest. General Strachey resided in India for many years, and made a life long study of the Geology and Geography of Central Asia. He was the principal authority of his time on this little explored continent and died February 12, 1908, at the age of 91 years.

"Scientific investigation has clearly shown that, so far as the main characteristics of the mountains are concerned, the natural boundaries of the Himalayan system must be carried much farther than had at first been

recognized. Considerable obscurity still involves the eastern portion of these mountains, and there is great want of precise knowledge as to their connection with the ranges of western China, from which are thrown off the great rivers of China, Siam, and Burmah. On the west, however, it has been completely established that a continuous chain extends beyond the Indus along the north of the Oxus, and ends in that quarter about 68° E. long. In like manner it is found that no separation can be established, except a purely arbitrary one, between the Himalaya as commonly defined and the greatly elevated and rugged table-land of Tibet; nor between this last and the mountain ranges which form its northern border along the low-lying desert regions of central Asia.

"It thus appears that the Himalaya, with its prolongation west of the Indus, constitutes in reality the broad mountainous slope which descends from the southern border of the great Tibetan table-land to the lower levels of Hindustan and the plains of the Caspian; and that a somewhat similar mountain face, descending from the northern edge of the tableland, leads to another great plain on the north, extending far to the eastward, to the northern borders of China. Towards its northwest extremity this great system is connected with other mountains—on the south, with those of Afghanistan, of which the Hindu-Kush is the crest, occupying a breadth of about 250 miles between Peshawur and Kunduz; and on the north, with the mountains that flank the Jaxartes or Sir on the north, and the Thian-shan or Celestial Mountains. The eastern margin of Tibet descends to western China, and the south-eastern termination of the Himalaya is fused into the ranges which run north and south between the 95th and 100th meridians, and separate the rivers of Burmah, Siam, and western China.

"Nor can any of the numerous mountain ranges which constitute this great elevated region be properly regarded as having special, definite, or separate existence apart from the general mass of which they are the component parts; and Tibet cannot be rightly described, as it has been, as lying in the interval between the two so-called chains of the Himalaya and the Kouenlun or Kara Koram. It is in truth the summit of a great protuberance above the general level of the earth's surface, of which these alleged chains are nothing more than the south and north borders, while the other ranges which traverse it are but corrugations of the mass more or less strongly marked and locally developed.

"The average level of the Tibetan tableland may be taken at about 15,000 feet above the sea. The loftiest points known on the earth's surface are to be found along its southern or Himalayan boundary; one of them falls very little short of 30,000 feet in elevation, and peaks of 20,000 feet bound the entire chain. The plains of India which skirt the Himalayan face of the tableland, for a length of rather more than 1,500 miles, along the northern border of British India, nowhere rise so much as 1,000 feet above the sea, the average being much less. The low lands on the north, about Kashgar and Yarkend, have an elevation of from 3,000 to 4,000 feet, and no part of the Central Asiatic desert seems to fall below 2,000 feet, the lake of Lob-nor being somewhat above the level. The greatest dimen-

sion of the Tibetan mountain area from east to west may be about 2,000 miles, while its average breadth somewhat exceeds 500 miles; about 100 miles on either side constitute the sloping faces, the central tableland having a width of about 200 miles on the west and probably 500 miles at its eastern border."

General Strachey thus shows that the Himalayan mountains and Tibetan Plateaus are directly and intimately connected as merely different parts of one great continuous movement of the earth's crust.

After describing many features of the Himalayas, General Strachey continues:

"The general conclusion that may be drawn from the facts of structure thus briefly indicated is that the elevation of the Himalaya to its present great height is of comparatively recent occurrence. An area of land must have existed where the main line of snowy peaks now stands, which has not been submerged since the Palæozoic period, and which then had its northern boundary somewhere along what has been termed the Indian watershed. Evidence of a similar ancient sea on the south also exists, but in less definite shape; and whether it was united with the northern sea or not is still a matter of conjecture, though the distinctive character of the fossils rather indicates that there was no direct union. The possible connection of this ancient Himalayan land area with the pre-Tertiary land of the peninsula of India is also only a matter for speculation.

"There is further reason to infer that the existence of the great line of peaks is rather due to some previous line of elevation on the ancient land, which has continued to retain its relative superiority while the whole areas have been raised, rather than to any special line of energy of upheaval of recent date; and that the fundamental features of its former configuration of surface in mountain and valley have been preserved throughout. There is evidence for the conclusion that the chief rivers of the pre-Tertiary land issued from the mountains where the present main streams are found, and this embryo Himalaya may have been of such moderate height as to have permitted the passage across it of the Siwalik mammals, the remains of which appear both on the border of the Indian plain and in Tibet. It is after the middle Tertiary epoch that the principal elevation of these mountains must have taken place, and about the same time also took place the movements which raised the tablelands of Afghanistan and Persia, and gave southern Asia its existing outlines.

"The best answer that can be given to an inquiry as to how changes of level could have arisen, such as those which are observed in the Himalaya, is that they should be regarded as due rather to secondary actions consequent on the general contraction of the cooling terrestrial sphere than to direct elevating forces, for which no known origin can be assigned. The contraction of the cooling but now solid crust of the earth must have set up great horizontal strains, partly of tension and partly of compression

which would necessarily have been followed by rupture or crushing along lines of least resistance, and the movements on such lines are marked by the great mountain ranges that traverse the surface. A dislocation of the solid crust of the earth once having taken place, it would probably continue to be a line of least resistance ever after, and a succession of movements during past geological periods may thus be reasonably expected along such lines. Somewhat in proportion as the disturbing forces are intense, and the thickness of the crust on which they act is great, will be the tendency of the lines of rupture to be continuous for a considerable distance; and as the disturbed area is extended in its dimensions, the probability will increase of a repetition of a series of similar dislocations on lines approximately parallel to, or at right angles to, one another and to the line on which the greatest compression and consequent tension take place. In a disturbed area, one transverse dimension of which is sensibly greater than the rest, the longitudinal ruptures will predominate in the interior and the transverse towards the borders. Almost all mountains give indications of having been shaped by forces thus related, and to the action of such forces may the main characteristics of the structure of the Himalaya, and the arrangement of its ridges and valleys be attributed. Whatever may be the power of rivers in general as instruments of erosion, and whatever effect the Himalayan rivers have had in removing the fragments of the rocks over and among which they took their courses, it is hardly possible to doubt that their main directions were determined by the anterior lines of dislocation which opened up hollows down which they could flow, and which must invariably have been accompanied by a destructive and crushing action on the rocks along them, which has enabled the waters the more readily to sweep away the obstacles in their path. The parallelism of many of the great Tibetan and Himalayan rivers for hundreds of miles together, and such mountains, seems wholly inexplicable in any other manner." (Ency. Brit., p. 828.)

This account is quite clear and satisfactory, except that part of it which deals with the cooling and contraction of the globe. Here General Strachey has made the best of a very inadequate hypothesis.

Just as the Andes were formed by expulsions of lava from under the Pacific, so also here the Himalayas were formed by a corresponding movement due mainly to the Indian Ocean, which has also raised high mountains along the eastern border of Africa. We cannot yet give all the details of the Himalayan development, but in general it is evident that it was similar to that of the Andes. The uplift of the great plateau of Tibet corresponds to that of Titicaca. And the parallel ranges of the Himalayas originated by the usual process of the folding up of successive sea trenches. On the

outside of these mountains there still remain trough-like depressions where the Indus, Ganges and Brahmaputra now flow. The undermining produced in raising the Himalayan embankment still shows in the valleys to the south, though the sea has receded; and the great earthquake belt south of the Himalayas still discloses to us the nature of the forces which produced this mighty uplift.

The following critical passages by General Strachey are also of decided interest:

"The great peaks are, with few exceptions, composed of schistose rock, though granite veins may be seen in the mountain faces to very great elevations; one of these exceptions is the great peak of Kamet in Kumaon, which rises to about 25,000 feet in what appears to be a mass of grey granite.

"Passing to the north of the line of great peaks the metamorphosed schists are suddenly replaced by slates and limestones, which are in many places highly fossiliferous, exhibiting what appears to constitute in the aggregate a fairly continuous series from the Lower Silurian to the Cretaceous formations, though the complete sequence has not been observed in any one locality. The western region of the Himalaya alone has been sufficiently explored to admit of any positive statements, but the indications gathered from such imperfect accounts and other data as exist relative to the eastern parts of the mountains leave little doubt that the change observed in the west on approaching and entering Tibet holds good on the east also, and that the general physical features of the whole tract are much alike, though doubtless with many differences in detail.

"The fossiliferous strata of western Tibet are continued, though perhaps with some breaks, to the Tertiary period. In certain localities nummulitic rocks, probably Eocene, have been observed, and from the great alluvial deposit which forms the plain of Gugé, already noticed, the remains of mammals, apparently of Siwalik age, have also been obtained. Among these were bones of the elephant and rhinoceros, the existence of which, in the present condition of these regions, would be wholly impossible; so that there is no room to doubt that these deposits have been raised from a comparatively low level to their existing great elevation of upwards of 15,000 feet, since they were laid out. As in the case of the plain of India, we here, too, have no complete proof of the origin of these great nearly horizontal deposits, but it seems clear, from the materials of which they are formed, that they must have been laid out by the water, either by the sea or some great inland lake. They are largely composed of boulder deposits, and large boulders are strewn over the surface imbedded in the ground in a manner that seems only explicable as the result of the action of a considerable body of water.

"Several lines of granitic and eruptive rock occur in western Tibet, of which all that need here be said is that they appear all to be older than the Tertiary alluvium, but some of them are possibly contemporaneous with the nummulitic and older formations." (Ency. Brit. p. 828.)

In an earlier passage, after comparing some of the smaller Himalayan ranges to the Swiss Alps, General Strachey adds:

"To obliterate these two ranges from the Himalaya would make no very sensible inroad on it, though they surpass in bulk the whole of the Swiss Alps; and it is no exaggeration to say that, along the entire range of the Himalaya, valleys are to be found among the higher mountains into which the whole Alps might be cast without producing any result that would be discernible at a distance of ten or fifteen miles. And it is important to bear in mind these relations of magnitude, for the terms at our disposal in the description of the mountains are so limited that it is necessary to employ the words chain, range, ridge, spur, etc., rather with reference to relative than to absolute importance, so that the scale of our nomenclature changes with the extent and altitude of the mountains of which we speak." (Ency. Brit., p. 827.)

§ 36. *The Alps*.—In the *Encyclopedia Britannica*, article "Alps," by John Ball, we find the following brief outline of the salient features:

"Accurate knowledge of the Alps is so recent that few attempts have been made to establish a general division of the entire region, and it cannot be said that any one arrangement has obtained such general recognition as not to be open to future modification; but there is a pretty general agreement as to the main features of that here proposed, to which a few general remarks must be premised.

"Whatever may have been the original cause of the disturbances of the earth's crust to which great mountain chains owe their existence, it is generally, though not universally, true that the higher masses (formed of crystalline rock and geologically more ancient) are found towards the central part, and that these are flanked by lower ranges, composed of more recent rocks, which surround the central groups very much as an outer line of entrenchment may be seen to surround a fort. In most cases it is not possible to descend continuously in a nearly direct line from the crest of a great mountain chain to the plains on either side, for there are usually intermediate valleys, running more or less parallel to the central range, which separate this from outer secondary ranges. These in turn, are often accompanied by external ranges, intermediate between them and the plains, and related to them as they are to the central ranges. The type of arrangement here described is more or less traceable throughout the greater part of the Alps, but is most distinctly exhibited in the eastern portion lying between the Adige and the frontier of Hungary. We have a central range, composed mainly of crystalline rock; a northern range, formed of secondary rocks, separated from the first by the great valleys of the Inn, the Salza, and the Enns; a southern range, somewhat similar to the last in geological structure, divided from the central one by the Rienx, or east branch of the Adige, and the Drave. Flanking the whole, as an external entrenchment on the north side, are the outer ranges of the Bavarian Alps, of the Salzkam-

mergut, and of Upper Austria, to which corresponds on the south side the Monti Lessini, near Verona, the mountains of Recoaro, those of the Sette Comuni, and the considerable masses crowned by the summits of the Grappa, the Col. Vicentino, the Monte Cavallo, the Monte Matajur, and Monte Nanos. Where, as in the case above mentioned, the secondary ranges of the Alps rise to a greater altitude, and are completely separated from the neighbouring portions of the central chain, it is impossible not to distinguish them as distinct groups; but the outermost ranges, which rarely rise above the forest zone, are in all cases regarded as appendages of the adjoining groups. These outer ranges are called in German Voralpen, and in Italian Prealpi." (Ency. Brit., p. 623.)

Again on page 620, this author remarks:

"In every mountain system geographers are disposed to regard the watershed, or boundary dividing the waters flowing towards the opposite sides of the range, as marking the main chain; and this usage is often justified by the fact that the highest peaks lie on, or very near, the boundary so defined. In applying this term in the case of the Alps, there are, however, difficulties arising from their great extent and the number of their branches and ramifications. Many of the loftiest groups lie altogether on one side of that which we call the main chain, and at the eastern extremity, where all drainage is ultimately borne to the Black Sea, we must be partly guided by geological considerations in deciding which of several ranges deserves to be considered pre-eminent." (Vol. I., p. 620.)

Sir Archibald Geikie's discussion of the origin of the Alps, in the article "Geology," *Encyclopedia Britannica* (pp. 373-374), bears on the problem now before us:

"The Alps, on the contrary, present an instructive example of the kind of scenery that arises where a mass of high ground has resulted from the intense corrugation and upheaval of a complicated series of stratified and crystalline rocks, subsequently for a vast period carved by rain, frost, springs and glaciers. We see how, on the outer flanks of those mountains among the ridges of the Jura, the strata begin to undulate in long wave-like ridges, and how, as we enter the main chain, the undulations assume a more gigantic tumultuous character, until, along the central heights, the mountains lift themselves towards the sky like the storm-swept crests of vast earth billows. The whole aspect of the ground suggests intense commotion. Where the strata appear along the cliffs or slopes they may often be seen twisted and crumpled on the most gigantic scale. Out of this complicated mass of material the sub-aerial forces have been ceaselessly at work since its first elevation. They have cut valleys, sometimes along the original depressions, sometimes down the slopes. They have eroded lake-basins, dug out corries or cirques, notched and furrowed the ridges, splintered the crests, and have left no part of the original surface unmodified. But they have not effaced all traces of the convulsions by which the Alps were upheaved."

In his account of the Miocene ("Text-book of Geology," p. 1261, edition of 1903), Geikie says:

"The Gulf of Gascony then swept inland over the wide plains of the Garonne, perhaps even connecting the Atlantic with the Mediterranean by a strait running along the northern flank of the Pyrenees. The sea washed the northern base of the now uplifted Alps, sending, as in Oligocene time, a long arm into the valley of the Rhine as far as the site of Mainz, which then properly stood at the upper end, the valley draining southward instead of northward. The gradual conversion of salt into brackish and fresh water at the head of this inlet took place in Miocene time. From the Miocene firth to the Rhine, a sea-strait ran eastwards, between the base of the Alps and the line of the Danube, filling up the broad basin of Vienna, sending thence an arm northwards through Moravia, and spreading far and wide among the islands of southeastern Europe, over the regions where now the Black Sea and Caspian basins remain as the last relics of this Tertiary extension of the ocean across southern Europe. The Mediterranean also still presented a far larger area than it now possesses, for it covered much of the present lowlands and foot-hills along its northern border, and some of its important islands had not yet appeared or had not acquired their present dimensions."

On pages 1371-2 of Geikie's "Geology," we find the following interesting passages:

"*Alpine Type of Mountain Structure.*—It is along a great mountain chain like the Alps that the most colossal crumplings of the terrestrial crust are to be seen. In approaching such a chain, one or more minor ridges may be observed running on the whole parallel with it, as the heights of the Jura flank the north side of the Alps, and the sub-Himalayan hills follow the southern base of the Himalayas. On the outer side of these ridges, the strata may be flat or gently inclined. At first they undulate in broad gentle folds; but traced towards the mountains these folds become sharper and closer, their shorter sides fronting the plains, their longer slopes dipping in the opposite direction. This inward dip is often traceable along the flanks of the main chain of mountains, younger rocks seeming to underlie others of much older date. Along the north front of the Alps, for instance, the red molasse is overlain by Eocene and older formations. The inversions and disruptions increase in magnitude till they reach such colossal dimensions as those of the Glärnisch, where pre-Cambrian schists, and Triassic, Jurassic, and Cretaceous rocks have been driven for miles over the Eocene and Oligocene flysch (pp. 677, 693). In such vast crumplings and thrusts it may happen that portions of older strata are caught in the folds of later formations, and some care may be required to discriminate the enclosure from the rocks of which it appears to form an integral and original part. Some of the recorded examples of fossils of an older zone occurring by themselves in a much younger group of plicated rocks may be thus accounted for.

"The inward dip and consequent inversion traceable towards the center of a mountain chain lead up to the fan-shaped structure (p. 678) where the oldest rocks of a series occupy the center and overlie younger masses, which plunge steeply under them. Classical examples of this structure occur in the Alps (Mont Blanc, Fig. 258, St. Gothard), where crystalline rocks such as granite, gneiss, and schists, the oldest masses of the chain, have been ridged up into the central and highest peaks. Along these tracts, denudation has been of course enormous, for the appearance of the granitic rocks at the surface has been brought out, not necessarily by actual extrusion into the air, but more probably by prolonged erosion, which in these higher regions, where many forms of sub-aerial waste reach their most vigorous phase, has removed the vast overreaching cover of younger rocks under which the crystalline nucleus doubtless lay buried."

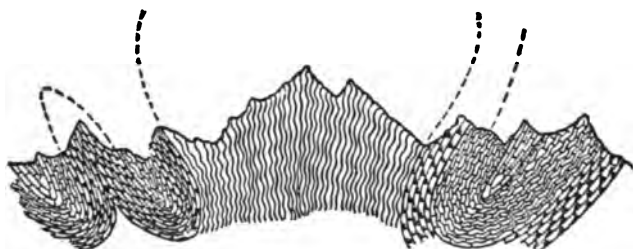


FIG. 13. Fan-shaped Structure, Central Alps.

Again on page 1372, we read:

"A mountain chain may be the result of one movement, but probably in most cases is due to a long succession of such movements. Formed on a line of weakness in the crust, it has again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval. Successive stages of uplift are usually not difficult to trace. The chief guide is supplied by unconformability. . . .

"In most great mountain chains, however, the rocks have been so intensely crumpled, dislocated, and inverted, that much labor may be required before their true relations can be determined.

"The Alps offer an instructive example of a great mountain system formed by repeated movements during a long succession of geological periods. The central portions of the chain consist of gneiss, schists, granite, and other crystalline rocks, partly referable to the pre-Cambrian series, but some of which (Schistes lustrés, Bündnerschiefer) include metamorphosed Palæozoic, Secondary, and in some places, perhaps, even older Tertiary deposits (pp. 802, 1099). It would appear that the first outlines of the Alps were traced out even in pre-Cambrian times, and that after submergence, and the deposit of Palæozoic formations along their flanks, if not over most of their site, they were reelevated into land. From the relations of the

Mesozoic rocks to each other, we may infer that several renewed uplifts, after successive denudations, took place before the beginning of Tertiary times, but without any general and extensive plication. A large part of the range was certainly submerged during the Eocene period under the waters of the wide sea which spread across the center of the Old World, and in which the nummulitic limestone and flysch were deposited. But after that period the grand upheaval took place to which the present magnitude of the mountains is chiefly due. The older Tertiary rocks, previously horizontal under the sea, were raised up into mountain-ridges more than 11,000 feet above the sea-level, and together with the older formations of the chain, underwent colossal plication and displacement. Enormous slices of the oldest rocks were torn away from the foundations of the chain and driven horizontally for miles until they came to rest upon some of the newest formations. The thick Mesozoic groups were folded over each other like piles of carpets, and involved in the lateral thrusts so as now to be seen resting upon the Tertiary flysch. So intense was the compression and shearing to which the rocks were subjected that lentils of the Carboniferous series have been folded in among Jurassic strata, and the whole have been so welded together that they can hardly be distinguished where they meet, and what were originally clays and sands have been converted into hard crystalline rocks. It is strange to reflect that the enduring materials out of which so many mountains, cliffs, and pinnacles of the Alps have been formed are of no higher geological antiquity than the London Clay and other soft Eocene deposits of the south of England and the north of France and Belgium. At a later stage of Tertiary time, renewed disturbance led to the destruction of the lakes in which the molasse had accumulated, and their thick sediments were thrust up into large broken mountain masses, such as the Rigi, Rossberg, and other prominent heights along the northern flanks of the Alps. Since that last post-Eocene movement, no great orogenic paroxysm seems to have affected the Alpine region. But the chain has been left in a state of unstable equilibrium. From time to time normal faults have taken place whereby portions of the uplifted rocks have sunk down for hundreds of feet, and some of these dislocations have cut across the much older and more gigantic displacements of the thrust-planes (Fig. 282). At the same time continuous denudation has greatly transformed the surfaces of the ground, so that now cakes of gneiss are left as mountainous outliers upon a crushed and convoluted platform of Tertiary strata. Nor, in spite of the settling down of these broken masses, has final stability been attained. The frequent earthquakes of the Alpine region bear witness to the strain of the rocks underneath, and the relief from it obtained by occasional rents propagated through the crust along the length of the chain."

In view of the explanation of the folding of the Alps given in § 28, we need not comment on these views. They confirm the theory outlined in this paper, that the plications of all such chains must be sought in the actions of the sea, and mainly while the

range is under water, and not at all in the secular cooling of the globe.

V. COMPARISON OF THE OLD AND NEW THEORY OF MOUNTAIN FORMATION CONTINUED.

(B) VIEWS OF EMINENT GEOLOGISTS ON MOUNTAIN FORMATION IN GENERAL.

§ 37. *Elie de Beaumont's Theory of the Secular Cooling and Collapse of the Globe.*—This venerable theory is thus condensed by Lyell:

"The origin of these chains depends not on partial volcanic action or a reiteration of ordinary earthquakes, but on the secular refrigeration of the entire planet. For the whole globe, with the exception of a thin envelope, much thinner in proportion than the shell to an egg, is a fused mass, kept fluid by heat, but constantly cooling and contracting in dimensions. The external crust does not gradually collapse and accommodate itself century after century to the shrunken nucleus, subsiding as often as there is a slight failure of support, but it is sustained throughout whole geological periods, so as to become partially separated from the nucleus until at last it gives way suddenly, cracking and falling in along determinate lines of fracture. During such a crisis the rocks are subjected to great lateral pressure, the unyielding ones are crushed, and the pliant strata bent, and are forced to pack themselves more closely into a smaller space, having no longer the same room to spread themselves out horizontally. At the same time, a large portion of the mass is squeezed upwards, because it is in the upward direction only that the excess in size of the envelope, as compared to the nucleus can find relief. This excess produces one or more of those folds or wrinkles in the earth's crust which we call mountain-chains."

De Beaumont's theory is given more from its antiquity than from its present day importance, and yet in some form it still holds its place in all our treatises on geology. Indeed the latest works include discussions of the strength of domes, as if the nucleus of the globe were shrinking away from the crust, and the latter thus subjected to crushing from its own weight.

§ 38. *Views of Lyell.*—This great geologist always rejected Elie de Beaumont's theories of mountain formation, and gave the most cogent reasons for his course. He adopted the theory that the land is occasionally depressed and elevated, by internal forces, but did not definitely decide what forces produced these progressive

or oscillatory movements of the earth's crust. One of Lyell's greatest disciples was Charles Darwin, whose views we shall now very briefly recall.

§ 39. *Views of Charles Darwin.*—The views of Darwin are very briefly and lucidly set forth by Professor Suess ("Face of the Earth," Vol. I, p. 104), as follows:

"The earthquake of February 20, 1835 (at Concepcion, Chili), gave rise to one of the most important works on the elevation of mountains, indeed I may say to the the only attempt, based on direct observation of nature, to establish more exactly the older theories concerning the force which is supposed to have raised up mountain chains. The author of this work is Charles Darwin. Since that time no second attempt, or at least no attempt of equal importance, has been made in this direction. To day, more than half a century later, it is possible to hold other opinions on these questions and yet to recognize the boldness of the generalization which even then revealed the master.

"Darwin saw the awakening activity of the volcanoes during and after the earthquake; he believed he saw elevation, although not uniform elevation of the solid ground; in addition he saw the terraces along the coast. But he also knew that similar terraces occur on the east coast of South America, where there are no volcanoes and no earthquakes. The earthquakes must therefore have appeared to his eyes as the local expression of a universal force. The secular contraction of the earth, a theory already eagerly advocated by several investigators, Darwin justly held to be entirely unsuited to explain those intermittent elevations which the terraces betrayed, and thus he reached the conclusion:

"That the form of the fluid surface of the nucleus of the earth is subject to some change, the cause of which is entirely unknown and the effect of which is slow, intermittent but irresistible."

§ 40. *Views of Professor James D. Dana.*—The views of this eminent geologist have been carefully discussed in the paper on "The New Theory of Earthquakes and Mountain Formation as Illustrated by Processes Now at Work in the Depths of the Sea," § 13. The reader is referred to that discussion. Here it must suffice to say that, although Dana recognized that there was a fundamental relationship between the depth and extent of an ocean and the height of the mountains which surround it, he was unable to define this relationship except in very general terms, and could not assign any definite cause for the law which he pointed out. He considered the oceanic basins as subsiding, while the continents were being elevated.

Though Dana's views were somewhat modified by later study and investigation, he always maintained that "the principal mountain chains are portions of the earth's crust which have been pushed up and often crumpled or plicated by lateral pressure resulting from the earth's contraction." In order to explain this supposed mode of action he held that the oceanic areas have been "the regions of greatest contraction and subsidence, and that their sides have been pushed like the ends of an arch, against the borders of the continents."

Even with these arbitrary assumptions it is not at all clear how the settlement of the Pacific Ocean could elevate our great plateau west of the Rocky Mountains, which is nearly a thousand miles wide. If the subsidence of the ocean bed had pushed up the margin of North America, the crumpling and elevation of the land could not well extend one third of the way across the continent. We need not, however, be greatly surprised at this difficulty, for at best Dana's theory is vague, and he evidently could not understand just how the elevation had come about. Yet so fully was Dana convinced of the dependence of the mountains on the oceans adjacent to them that he reduced it to calculation by the rule-of-three. He says:

"The relation of the oceans to the mountain borders is so exact that the rule-of-three form of statement cannot be far from the truth. *As the size of the Appalachians to the size of the Atlantic, so is the size of the Rocky chain to the size of the Pacific. Also, as the height of the Rocky chain to the extent of the North Pacific, so are the height and boldness of the Andes to the extent of the South Pacific.*" ("Manual of Geology," 1863, p. 25.)

This was indeed a remarkably near approach to the great law of nature, that the mountains along the coasts are formed by the expulsion of lava from under the sea, and are, therefore, everywhere proportional to extent and depth of the adjacent oceans.

§ 41. *Views of James Hall.*—In 1857 this distinguished American geologist announced in a presidential address to the American Association at Montreal, that the enormous depth of the sedimentation along the Appalachian chain was due to the prolonged accumulation of sediments along a sinking, off-shore line of sea bottom. He reached this view from the careful study of the

Appalachian and other American mountain regions. To explain such deposits he supposed that marine currents had formerly traversed these regions and by gradually depositing sediments of great weight had also sunk the crust till at length a great thickness was attained. When the rocks thus formed had become solidified and crystallized the borders of the continent were afterwards up-raised somehow. He did not indicate how the uplift had come about, nor did he think that the mountain regions had been raised separately. Denudation had then commenced, and finally given the mountains the forms they have today.

Keferstein, Sir John Herschel, Dr. T. Sterry Hunt and others, along with Hall, or even before him, in some cases, had developed the theory of aqueo-igneous fusion, which was supposed to produce a plastic zone between the consolidated crust and the solid nucleus. This theory supposed that the isogeotherms rise in regions of heavy sedimentation. Hall held that this would

"cause the bottom strata to establish lines of weakness or of least resistance in the earth's crust, and thus determine the contraction which results from the cooling of the globe to exhibit itself in those regions, and along those lines where the ocean's bed is subsiding beneath the accumulated sediments."

Many of the views afterwards more fully developed by Leconte are here faintly traced by Hall, and for that reason these early views of mountain formation are worthy of attention.

§ 42. *Views of Leconte.*—This veteran geologist gave great attention to mountain formation throughout a long career, and his residence on the Pacific Coast gave him exceptional facilities for studying the ranges of our western states, and especially of California, which includes the most remarkable developments in North America. The views at which Leconte arrived, as set forth in his "Elements of Geology," edition of 1896, are as follows:

"Mountain Origin.

"Leaving aside for the present all disputed points, it is now universally admitted that mountains are not usually pushed up by a vertical force from beneath, as once supposed, but are formed wholly by *lateral pressure*. The earth's crust along certain lines is *crushed together* by lateral or horizontal pressure and rises into a mountain-range along the line of yielding, and to a height proportionate to the amount of mashing. But the yielding is not by rising into a hollow arch, nor into such an arch filled beneath with liquid

(for in neither case would the arch support itself), but by mashing together and in thickening and crumpling of the strata and an upswelling of the whole mass along the line of greatest yielding. That this is the immediate or *proximate* cause of the origin or elevation of mountains is plainly shown by their structure. As to the *ultimate cause*—*i. e.*, the cause of the enormous lateral pressure—this lies still in the field of discussion. We shall discuss it briefly in its proper place" (pp. 261-2).

Again, on page 264, we find this account:

"*Proof of Elevation by Lateral Pressure alone: 1. Folding.*—It is evident that foldings such as those represented in all the above figures, and which occur in nearly all mountains, cannot be produced except by lateral pressure, and are therefore proof of such pressure. But, moreover, it can be shown that, when we take into consideration the immense thickness of mountain strata and the degree of folding, lateral pressure is *sufficient* to account for the whole elevation, without calling in the aid of any upward pushing from beneath. For example, the Coast range of California (Fig. 228) is composed of at least five anticlines and corresponding synclines. If

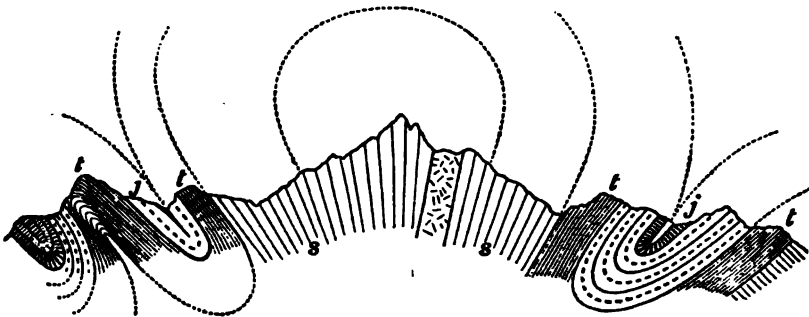


FIG. 14. Section of a Portion of the Alps.

its folded strata were spread out horizontally in the position of the original sediments, they would undoubtedly cover double the space. Now, supposing the strata here are only 10,000 feet thick—a very moderate estimate—in mashing to one half the extent, they would be thickened to 20,000 feet, which would be a clear elevation of 10,000 feet if they were not subsequently eroded. According to Renevier, a section of the Alps reveals seven anticlines and corresponding synclines, and some of them are complete overfolds (Fig. 230). We are safe in saying that Alpine strata have been mashed horizontally into one half their original extent. Supposing these were originally 30,000 feet thick (they were really much thicker), this would make a clear elevation of 30,000 feet. Of course, most of this has been cut away by erosion. In the Appalachian range, according to Claypole, the foldings are so extreme that in one place 95 miles of original extent have been mashed into 16 miles, or six into one, and yet the Appalachian strata are estimated as 40,000 feet thick. Cases of still greater doubling of strata upon themselves occur. In

the Highlands of Scotland the strata by lateral thrust were broken and slidden one over another for ten miles. In the Canadian Rocky Mountains there is an overthrust of seven miles, by which the Cambrian is made to override the Cretaceous, and 50 miles of strata are mashed into 25 miles (McConnell). In the Appalachians of Georgia the *Rome fault* is an overthrust which brings the Cambrian in contact with the Carboniferous and the fault under different names may be traced northward for 275 miles; and in the Cartersville thrust-fault there is an overriding of 11 miles (Hayes). The manner in which this is done is illustrated on a previous page (Fig. 209). Evidently, then, the whole height of the mountains mentioned above is due to lateral crushing alone."

If Professor Leconte had been familiar with the folding produced in the sea trenches he could have completed the theory of mountain formation developed in this paper. As geologists have for centuries recognized the fossils found in mountains as having been deposited in the sea, it is remarkable that the suggestion seems never to have occurred to them that the folding was done in the sea before the land was lifted above the water, and by earthquake processes due to the sea itself. Leconte, however, came very near this view, as the following will show (p. 267 et seq.):

"*Mountains are made out of lines of thick sediments.*—But the question occurs, What determines the place of a mountain-range? The answer is, A mountain-range while in preparation—before it became a range—was a line of very thick sediments. This is a very important point in the theory of mountain origin, and therefore must be proved. The strata of all mountains, where it is possible to measure them, are found to be of enormous thickness. The strata involved in the folded structure of the Appalachian, according to Hall, are 40,000 feet thick, the strata exposed in the structure of the Wahsatch, according to King, are more than 50,000 feet thick; the Cretaceous strata of the Coast Range, near the Bay of San Francisco, according to Whitney, are 20,000 feet thick; and if we add to this 10,000 feet for the Eocene and Miocene strata, the whole thickness is probably not less than 30,000 feet, while the Cretaceous alone in Northern California, according to Diller, is 30,000 feet. The Alpine geologists estimate the thickness of the strata involved in the intricate structure of the Alps as 50,000 feet. The strata of Uintah, according to Powell, are 32,000 feet thick.

"Now, it must not be imagined that these numbers merely represent the *general* thickness of the stratified crust; only that in these places the strata are turned up and their edges exposed by erosion, and thus their thickness revealed. On the contrary, it may be shown that the same strata are much thinner elsewhere. The same strata which along the Appalachian range are 40,000 feet thick, when traced westward thin out to 4,000 feet at the Mississippi River. The same strata which along the line of the Wah-

satch are 30,000 feet thick, when traced eastward thin out to 2,000 feet in the region of the plains. It is evident, therefore, that mountain-ranges are lines of *exceptionally* thick strata.

"*Mountain-ranges were once Marginal Sea-Bottoms.*—Where, then, do sediments now accumulate in greatest thickness? Evidently on marginal sea-bottoms, off the coasts of continents. The greater part of the washings of continents are deposited within 30 miles of shore, and the whole usually within 100 miles. From this line of thickest and coarsest deposit the sediments grow thinner and finer as we go seaward. But evidently such enormous thicknesses as 40,000 feet cannot accumulate in the same place *without pari passu subsidence* such as we know takes place now whenever exceptionally abundant sedimentation is going on (p. 145). Therefore, *mountain-ranges before they were yet born*—while still in preparation as embryos in the womb of the ocean—*were lines of thick off-shore deposits gradually subsiding*, and thus ever renewing the conditions of continuous deposits.

"As this is a very important point, it is necessary to stop here awhile in order to show that such was actually the fact in the case of all the principal ranges of the American Continent—*i. e.*, that for a long time before they were actually formed, the places which they now occupy were marginal sea-bottoms receiving abundant sediments from an adjacent continent. We shall be compelled to anticipate some things that belong to Part III, but we hope to make statements so general that there will be no difficulty in understanding them.

"1. *Appalachian.*—The history of this range is briefly as follows: At the beginning of the Palæozoic era there was a great V-shaped land-mass, occupying the region now covered by Labrador and Canada, then turning northwestward from Lake Superior and extending perhaps to polar regions about the mouth of the Mackenzie River. This is shown on map, Fig. 269, on page 303. There is another great land-mass occupying the present place of the eastern slope of the Blue Ridge and extending eastward probably far beyond the present limits of the continent—as shown in the same figure by dotted line in the Atlantic Ocean. The western coast-line of this land-mass was the present place of the Blue Ridge. Westward of this line extended a great ocean—'the interior Palæozoic Sea.' The Appalachian range west of the Blue Ridge was then the *marginal bottom of that sea*. During the whole of the Cambrian, Silurian, and Devonian, this shoreline remained nearly in the same place, although there was probably a slow transference westward. Meanwhile, throughout this immense period of time, the washings from the land-mass eastward accumulated along the shore-line, until 30,000 feet of thickness was attained. At the end of the Devonian some considerable changes of physical geography of this region took place, which we will explain when we come to treat of the history of this period. Suffice it to say now that during the Carboniferous the region of the Appalachian was sometimes above the sea as a coal-swamp, and sometimes below, but all the time receiving sediment until 9,000 or 10,000 feet more of thickness was added, and the aggregate thickness became

40,000 feet. Of course, it is impossible that such thickness could accumulate on the same spot without *pari passu* subsidence of the sea-floor. In fact, we have abundant evidences of comparatively shallow water at every step of the process—evidence sometimes in the character of the fossils, sometimes in the form of shore-marks of all kinds, sometimes in the form of seams of coal, showing even swamp-land conditions. Again, of course, the sediments were thickest and coarsest near the shore-line, and thinned out and became finer towards the open sea, *i. e.*, westward. Finally, after 40,000 feet of sediments had accumulated along this line the earth-crust in this region gave way to lateral pressure, and the sediments were mashed together and folded and swollen up into the Appalachian range. Subsequent erosion has sculptured it into the forms of scenic beauty which we find there to-day.

"2. *Sierra*.—This was apparently the *first-born* of the Cordilleran family. Its history is as follows: During the whole Palæozoic and earlier part of the Mesozoic, there was in the Basin region a land-mass, whose form and dimensions we yet imperfectly know, but whose Pacific shore-line was *east of the Sierra*. The Sierra region was therefore at that time the marginal bottom of the Pacific Ocean. Probably the position of this shore line changed considerably at the end of the Palæozoic. The extent of this change we will discuss hereafter. Suffice it to say now that, during the whole of this time, the Sierra region received sediments from this land-mass until an enormous thickness (how much we do not know, because the foldings are too complex to allow of estimate) was accumulated. At last at the end of the Jurassic, the sea floor gave way to the increasing lateral pressure along the line of thickest sediments, and these latter were crushed together with complex foldings and swollen up into the Sierra. An almost inconceivable subsequent erosion has sculptured it into the forms of beauty and grandeur which characterize its magnificent scenery.

"3. *Coast Range*.—The birth of the Sierra transferred the Pacific shore-line westward, and the waves now washed against the western foot of that range, or possibly even farther westward in the region of the Sacramento and San Joaquin plains. At this time, therefore, the region of the Coast Range was the marginal bottom of the Pacific Ocean. During the whole Cretaceous, Eocene, and Miocene, this region received abundant sediments from the now greatly enlarged continental mass to the eastward; until finally, at the end of the Miocene, when 30,000 feet of sediments had accumulated along this line, the sea-floor yielded to the lateral pressure, and the Coast Range was born; and the coast-line transferred to near its present position.

"4. *Wahsatch*.—The physical geography of the region to the east of the Wahsatch (Plateau region) during Jura-Trias time is little known. But during the Cretaceous the region of the Wahsatch was the western marginal bottom of the great interior Cretaceous Sea (see map, Fig. 760, p. 486), receiving abundant sediments from the great land-mass of the Basin and Sierra region. This greatly increased the enormous thickness of sediments already accumulated along this line in earlier times. At the end of the Cretaceous the sediments yielded, and the Wahsatch was born. It is necessary, however, to say that both the Sierra and Wahsatch underwent very

great changes of form produced by a different process and at a much earlier period. We shall speak of this later.

"5. *Alps*.—Mr. Judd has recently shown that the region of the Alps, during the whole Mesozoic and Early Tertiary, was a marginal sea bottom, receiving sediments until a thickness was attained not less than that of the Appalachian strata. At the end of the Eocene these enormously thick sediments were crushed together with complicated foldings and swollen upward to form these mountains and afterward sculptured to their present forms.

"The same may be said of the Himalayas and nearly all other mountains. We may, therefore, confidently generalize, and say that the place now occupied by mountain-ranges have been previous to their formation, places of great sedimentation, and therefore usually marginal *ocean bottoms*. In some cases, however, the deposits in interior seas or mediterraneans have yielded in a similar way, giving rise to more irregular ranges or groups of mountains." . . .

"*Why thick Sediments should be Lines of Yielding*.—Admitting, then, that mountains are formed by the squeezing together of lines of very thick sediments, the question still occurs, *Why does the yielding take place along these lines in preference to any others?* This is a capital point in the theory of mountain formation. The answer is as follows: We have already seen (p. 231) that accumulation of sediments causes the isotherm to rise and the interior heat of the earth to invade the lower portion of the sediments with their included waters. Now this invasion of heat in its turn causes hydrothermal softening or even fusion, not only of the sediments, but also of the sea-floor on which they rest. Thus a line of thick sediments becomes a line of softening and therefore a line of weakness, and a line of yielding to the lateral pressure, and therefore a line of mashing together and folding and upswelling—in other words a mountain-range. As soon as the yielding commences we have an additional source of heat in the crushing itself. In addition to this, upheaval by lateral crush by the tendency to arch the strata would produce relief of gravitative pressure, and therefore fusion (p. 103). It follows from this that there is or was beneath every mountain a line of fused or semi-fused matter. This we will call the *sub-mountain liquid*. This by cooling and solidification becomes a *metamorphic or granitic core*, which by erosion forms the metamorphic or granitic axis and crest of many great mountains" . . . (pp. 271-2).

"*Cause of Lateral Pressure*.—We have thus proved that the immediate cause of the origin and the growth of mountains is lateral pressure acting on thick sediments, crushing them together and swelling them up along the line of great thickness. But still the question remains, What is the *ultimate* cause, *i. e.*, the *cause of the lateral pressure?* This, as we have already said, lies still in the domain of doubt and discussion, but the view which seems most probable may be briefly stated as follows:

"In the secular cooling of the earth there would be not only unequal radial contraction, giving rise, as shown on page 175, to continents and ocean-basins, but also to unequal contraction of the *exterior* as compared with the *interior*. At first, and for a long time, the exterior would cool

fastest; but there would inevitably, sooner or later, come a time when the exterior, receiving heat from abroad (sun and space), as well as from within, would assume an almost constant temperature, while the interior would still continue to cool, and contract. Thus, therefore, after a while the interior nucleus would contract faster than the exterior shell. It would do so, partly because it would cool faster, and partly because the coefficient of contraction of a hot body is greater than that of a cooler body. Now, as soon as this condition was reached, the exterior shell, following down the shrinking nucleus, would be thrust upon itself by a lateral or horizontal pressure which would be simply irresistible. If the earth's crust were a hundred times more rigid than it is (thirty times as rigid as steel, 500 to 1,000 times as rigid as granite—Woodward, *Science*, Vol. XIV, p. 167, 1889), it must yield. Mountain-ranges are the lines along which the yielding takes place, and this yielding takes place along the lines of thick sediments because these are lines of weakness.

"There are several serious objections which may be brought against this view: 1. Calculations seem to show that the amount of crumpling and folding actually found in the mountains is many times greater than could be produced by the contraction of the earth by *cooling*. But it may be answered (1) that the calculations take no account of the greater coefficient of contraction at high temperatures, and therefore at great depths, (2) and that there may be *other causes* of contraction besides cooling. For example, loss of constituent gases and vapors from the interior of the earth, through volcanic vents and fissures, has been suggested by O. Fisher (p. 102).

"2. Again, it has been shown by Dutton that it is impossible that the effects of differential contraction should be concentrated along certain lines, so as to give rise to mountain-ranges without a shearing of the crust upon the interior portions, which is inadmissible if the earth be solid. Instead, therefore, of conspicuous mountain-ranges, the effects of differential contraction would be distributed all over the surface, and be wholly imperceptible. But in answer to this it may be said that there is no difficulty in the way of shearing, and therefore of such concentration of effects along certain lines, if *there be a sub-crust liquid or semi-liquid layer*, either universal or else underlying large areas of surface.

"Still other objections have been raised, but these are so recent that they have not yet been sufficiently sifted by discussion to deserve mention here.¹ The origin of mountains by lateral pressure is a fact beyond dispute. This is the most important fact for the geologist. How the lateral pressure is produced is a pure physical question which must be left to the physicists to settle among themselves" (pp. 274-5).

Lecoute treats also of Monoclinical mountains, as found in the Great Basin, which he explains by normal faulting, or vertical movement of crust blocks, and finally adds:

¹For a completer discussion of this subject, see "Theories of Mountain Origin," *Jour. Geol.*, Vol. I., p. 542, 1893.

"Thus, then, there are two types of mountains strongly contrasted, mountains of the one type are formed by lateral *pressure and crushing*, of the other type by lateral *tension and stretching*. The one gives rise mainly to reverse faults, the other always to normal faults. Mountains of the one type are formed by upswelling of thick sediments, those of the other type by irregular readjustment of crust-blocks. Mountains of the one type are *born of the sea*, those of the other type are *born on the land*. We find examples of the one type in nearly all the greatest mountains everywhere, but especially in the Appalachian, the Alps and the Coast Range. The best examples, perhaps the only examples, of the other type are the Basin ranges. Some mountains, as the Sierra, the Wahsatch, and certainly *some* of the Basin ranges, belong to both types. In their origin, they have formed in the first way, but afterward have been modified by the second way. Thus the first is the fundamental method, and the second only a modifying process" (p. 277).

These views of Leconte call for no special comment, beyond the remark that normal faulting itself is wholly unexplained. If secular cooling were the cause, such faults ought to occur east of the Rocky Mountains as well as west of them. The important difference is that the Pacific Ocean was on the west pushing up the land, and a continental basin on the east, either dry or covered by shallow water and therefore doing little or no pushing at all. In any case the great plateaus of the west were certainly uplifted by the Pacific, through the expulsion of lava under the land. In the Andes of South America the plateaus are higher indeed, but also narrower than those in North America, because in our continent the relief resulting from the leakage of the ocean took a broader and less elevated form. It is impossible for any one to doubt the identity of the forces which raised the Andes and their plateaus, the Himalayas and their plateaus, and the Rocky Mountains and the mountains and plateaus of the Great Basin. The principle of continuity shows clearly that the cause was everywhere one and the same. Several American geologists have suggested vertical uplifts in the Great Basin, from the way in which the crust blocks are displaced; but heretofore no known cause for such movements could be assigned, because it was held that secular cooling is the chief if not the only cause operating in the development of the globe.

§ 43. *Views of Rev. O. Fisher.*—The Rev. O. Fisher was the first to show by long and patient research the total inadequacy of secular cooling to account for the observed height of mountains.

He showed that the mountains are hundreds of times higher than the cooling of the earth will explain. On this point his labors mark a distinct advance in geological science; for next in importance to establishing true theories is the overthrow of erroneous ones, which clears the ground for a fresh start. But notwithstanding the unanswerable character of Fisher's argument, the old theories have been retained by geologists as the best they could devise. Fisher's criticisms of geological theories are carefully thought out, and worthy of attention. He has always denied the entire solidity of the earth, holding that the movements noticed in mountains proved the existence of a mobile substratum beneath a crust some twenty miles thick. Here again he was certainly right, and it is difficult to see how such an obvious proposition could be denied.

We need not dwell on Fisher's views of mountain formation, because they imply convection currents within the earth, and these latter are certainly inadmissible, except just beneath the crust in earthquake movements, as developed in the theory set forth in this paper.

§ 44. *Views of Major C. E. Dutton.*—Like the Rev. O. Fisher, Major Dutton was one of the earliest authorities to question the adequacy of secular cooling to account for the wrinklins noticed in the earth's crust. Using the results of Fourier's solution for the variation of temperature, as developed in the work of Lord Kelvin, Dutton found that

"the greatest possible contraction due to secular cooling is insufficient in amount to account for the phenomena attributed to it by the contraction hypothesis. By far the larger portion of this contraction must have taken place before the commencement of the Palæozoic age. By far the larger portion of the residue must have occurred before the beginning of the Tertiary, and yet the whole of this contraction would not be sufficient to account for the disturbances which have occurred since the close of the Cretaceous."

Major Dutton concludes that "the determination of plications to particular localities presents difficulties in the way of the contractional hypothesis which have been underrated." He held that the localization of the plications could result only from a large amount of horizontal slipping of the crust over the nucleus, and the friction involved in this movement even over a liquid nucleus would be so great as to render the assumption a physical absurdity.

If wrinkling resulted from uniform cooling and consequently uniform shrinkage, the effect would be analogous to that of a withered apple, with small wrinkles all over it, instead of a surface presenting in one region a continuous system of folds extending from Cape Horn to Alaska, and in another, a zone a thousand miles wide, from the Appalachian to the Rocky Mountains, with scarcely any evidence of disturbance whatever.

In these considerations Major Dutton has forcibly expressed the difficulty of supposing that a mountain range is formed by the cooling of the earth contracting equally along all its radii. Such a supposed mode of formation of our ranges, folded and crumpled as they are, is clearly impossible; and Major Dutton shares with the Rev. O. Fisher the credit of having been the first to recognize the total inadequacy of the contraction theory.

It is remarkable that after this antiquated theory had been thus clearly disproved, it should have continued in use. No one seems to have been able to frame a theory based on any cause except secular cooling, till the present writer developed the theory based on the leakage of the oceans and the formation of mountains by the expulsion of lava under the land, which perfectly explains all the phenomena.

§ 45. *Views of Geikie.*—In the article "Geology," *Encyclopedia Britannica*, p. 375, we find the following statement of the contraction theory:

"There still remains the problem to account for the original wrinkling of the surface of the globe, whereby the present great ridges and hollows were produced.

"It is now generally agreed that these inequalities have been produced by unequal contraction of the earth's mass, the interior contracting more than the outer crust, which must therefore have accommodated itself to this diminution of diameter by undergoing corrugation. But there seems to have been some original distribution of materials in the globe that initiated the depressions on the areas which they have retained. It has been already pointed out (ante, p. 223) that the matter underlying the oceans is more dense than that beneath the continents, and that, partly at least, to this cause must the present position of the oceans be attributed. The early and persistent subsidences of these areas, with the consequent increase of density, seems to have determined the main contours of the earth's surface. . . .

"The effects of this lateral pressure may show themselves either in broad dome-like elevations, or in narrower and loftier ridges of mountains.

The structure of the crust is so complex, and the resistance offered by it to the pressure is consequently so varied, that abundant cause is furnished for almost any diversity in the forms and distribution of the wrinkles into which it is thrown. It is evident, however, that the folds have tended to follow a linear direction. In North America, from early geological times, they have kept on the whole on the lines of meridians. In the Old World, on the contrary, they have chosen diverse trends, but the last great crummings—those of the Alps, Caucasus, and the great mountain ranges of central Asia—have risen along parallels of latitude.

"Mountain chains must therefore be regarded as evidence of the shrinkage of the earth's mass. They may be the result of one movement, or of a long succession of such movements. Formed on lines of weakness in the crust, they have again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval."

Geikie's views may be considered the accepted views of geologists generally, and it will be seen that they rest on the theory of contraction due to secular cooling.

On the constitution of the globe Geikie quotes ("Geology," p. 73) from the paper of Arrhenius, "Zur Physik des Vulkanismus" (1900), the following theory of the illustrious Swedish physicist:

"If the rocks at the earth's surface have a density half that of the globe as a whole, and if the density continues to hold good for the magma that arises from the melting of these rocks, we must conceive the existence of a much denser substance in the earth's interior. On various grounds, such as the preponderance of iron in nature, both in meteorites and in the sun, and the phenomena of terrestrial magnetism, it may be inferred that this substance is metallic iron. In consequence of its greater density this iron will naturally be deeper than the rock magma, and on account of the high temperature must exist in a gaseous condition. Somewhere about a half of the planet therefore should consequently consist of iron, and of other metals mingled with it in smaller proportions. The semi-diameter of this gaseous iron-sphere will thus include about 80 per cent. of the earth's semi-diameter. Then will come about 15 per cent. of the gaseous rock magma, next to it the liquid rock-magma for a thickness of about 4 per cent. of the terrestrial semi-diameter, and lastly the solid crust, for which not more than 1 per cent. may be claimed" (pp. 404-5).

Referring to the light thrown on the constitution of the interior by the observation of waves propagated by earthquakes, Geikie also adopts the theory of Arrhenius, which is as follows:

"The density of much the largest part (reckoned linearly) of this interior, amounting, as above stated, to about 80 per cent. of the radius, must be nearly three times higher than that of quartz. Since now the mean velocity of transmission of earthquake waves in the interior of the

earth has been ascertained to amount to 11.3 kilometers per second, the compressibility of that region must be 31 times less than that of quartz, that is, eight times less than that of solid steel, according to Voigt. This is a figure of precisely that order of magnitude which was to be expected. We may well believe that at depths of more than 1,000 kilometers the compressibility of gaseous iron sinks down to some ten times less than that of steel.

"The interior of the earth, therefore, with the exception of a solid crust about 40 kilometers thick, consists of a molten magma 100 or 200 kilometers in depth which shades continuously inward into a gaseous center. The liquids and gases in the interior possess a viscosity and incompressibility such as permit them to be regarded as solid bodies. From these, however, they are distinguished in the first place by the fact that differentiations are possible to a considerable degree, the effects of which may long endure. In the second place, long continued pressures, when acting on a large enough scale, may produce great deformations. Further, the liquids must possess the property of great expansion on a diminution of the high pressure, thereby readily becoming fluid. The process must thus differ but little from a normal melting with increase of volume, and especially of fluidity, as well as with absorption of heat. And yet the condition of aggregation is not thereby altered."

Geikie remarks that the theory of Arrhenius accords well with geological requirements:

"With reference to the crust of the earth, it meets the constantly repeated objections of the geologists to whom the existence of a comparatively thin crust has always seemed an essential condition for the production of that crumpled and fractured structure which the rocks of the land so universally present. If the solid crust of the earth is allowed to be about 25 miles thick, we must conceive that in the lower four fifths of its mass the rocks are in a condition of latent plasticity. They lie much beyond the crushing strength which they exhibit at the surface. They are not crushed into powder as they would be under a similar strain above ground, but they are ready to yield to the deformations that may arise consequent upon adjustments of the gigantic pressure to which they are subjected. Hence the solid crust down as far as its structure has been disclosed abounds in proofs that it has undergone colossal plication and fracture, and that higher portions of it many square miles in extent have been thrust bodily over each other for many miles."

The last view here expressed by Geikie as to how the crust becomes thrust over itself for many miles is not, we think, well founded, because it is shown in this paper that all this folding and overlapping of the crust arises in the trenches dug out in the sea bottom by earthquakes. This crumpling and overthrusting of the crust certainly would not arise except for earthquakes produced by

the leakage of the oceans, to which mountain formation is due. Of course the plasticity of this layer beneath the crust contributes to the final result, but the leakage of the oceans, with the resulting earthquakes, supplies the deforming force.

§ 46. *Views of Professor Suess.*—In the “Face of the Earth” (Vol. I, p. 107) we find the following brief exposition of Professor Suess’ views:

“The dislocations visible in the rocky crust of the earth are the result of movements which are produced by a decrease in the volume of our planet. The tensions resulting from this process show a tendency to resolve themselves into *tangential* and *radial* components, and thus into horizontal (*i. e.*, thrusting and folding), and into vertical (*i. e.*, sinking) movements. Dislocations may therefore be divided into two main groups, of which one is produced by the more or less horizontal, the other by the more or less vertical relative displacement of larger or smaller portions of the earth’s crust.

“There are large areas in which the first, and others in which the second group predominates, and there are also regions in which both groups appear together, and in which an intimate connection may be recognized between them, the resolution of the movements in space having in these cases been less complete. This essential difference in the movements of the lithosphere may be clearly perceived from a comparative study of the structure of the Old World; nor has it escaped the notice of American geologists.

“‘The geological provinces of the Great Basin,’ remarks Clarence King, has suffered two different types of dynamic action: one in which the chief factor was evidently tangential compression, which resulted in contraction and plication, presumably in post-Jurassic time; the other of strictly vertical action, presumably within the Tertiary, in which there are few evidences or traces of tangential compression.’

“Our colleagues on the other side of the ocean have even gone a great deal further. After comparison of the folded Appalachian mountains with the depressed Basin Ranges, Gilbert had in 1875 already suggested the possibility that in the Appalachians the causes of movement were superficial, in the Basin Ranges deep-seated. We shall have an opportunity, when discussing the relation of the Alps to their northern foreland, of determining to what extent this supposition finds confirmation in Europe. We may however state at once that as a rule it is only the dislocations of the second group which are accompanied by volcanic eruptions.”

§ 47. *Views of Arrhenius.*—It is well known that this distinguished Swedish physicist holds that the earth’s interior is essentially gaseous (*cf.* § 45, above), but under the great pressure operating in the globe made to behave very nearly as a solid.¹ In his

¹ See Postscript, page 274.

paper "Zur Physik des Vulkanismus," published in 1900, Arrhenius points out that in fluids at high temperature, where no increase in volume takes place, the internal friction of the molecules rises with the temperature, so that the viscosity increases and the fluidity diminishes; that a similar effect is observable in both gases and liquids; that although gases have the highest and solids the lowest compressibility, nevertheless when a gas near its critical temperature passes into a liquid, through a trifling physical change, there is practically no change in the compressibility. The higher the pressure the smaller is the compressibility, and a gas above the critical temperature may be made to acquire the properties of a solid by pressure alone. Such a mass has great density, small compressibility, and large viscosity, so that it has the properties of a solid, though really an imprisoned gas.

At a depth of 40 kilometers Arrhenius says the temperature is about 1200° C., and the pressure about 10,840 atmospheres; and as these conditions would render nearly all ordinary minerals fluid, he concludes that below that depth the matter is molten, in the form of a magma—that is, a viscous and nearly incompressible liquid made to act nearly as a solid by pressure.

At greater depths the temperature is above the critical temperature of every known substance, as the pressure rapidly increases and the liquid magma becomes a gaseous magma with larger and larger viscosity, and smaller and smaller compressibility—in other words, an elastic solid with rigidity increasing with the depth.

VI. ABANDONMENT OF THE OLD THEORIES OF THE PHYSICS OF THE EARTH.

§ 48. *The Total Inadequacy of the Old Theories to Account for the Fault Movements near the Sea, which Raise Vertical Blocks and Walls of Granite¹ Thousands of Feet above the Water.*—The vast

¹ Andesite is the name used to designate the kind of granitic rock found in the Andes. Charles Darwin showed that all granitic rocks are closely related. In his "Text-book of Geology," edition of 1903, book II, Part II, § 7, pp. 230-260, Sir Archibald Geikie gives tables of the chemical compositions of all these rocks, which show very clearly their close relationship. When we use the term *granite* therefore we mean *granitic rock* in the wide sense.

vertical walls and blocks of granite so often lifted thousands of feet above the sea, with deep water all around their bases, frequently encountered in different parts of the world, cannot be explained except by the present theory. Thus along the west coast of Chili and Patagonia, from Cape Horn to Valparaiso, in the Straits of Magellan, as well as in the ranges of the Andes further from the coast, in the Sierras of California, and elsewhere these vertical uplifts are common. It is obvious that they cannot possibly be explained by the old theories depending on the shrinkage of the globe. But if lava is expelled from beneath the sea, owing to the secular leakage of the ocean bottom, and the crust is fractured and rent into blocks by the earthquake forces, some of these blocks would naturally be pushed upward, leaving vertical walls of granite thousands of feet high. Occasionally the blocks would be forced apart, leaving the sea pass between, as so often seen in Chili, Patagonia and Tierra Del Fuego. The Straits of Magellan no doubt arose in this way. As already remarked in § 27, Darwin describes similar breaks in the Andes further north, through which the sea once flowed, but they are now raised above the water. No doubt the time will come when Tierra Del Fuego will be joined solid to Patagonia, by uplifts which will cause the sea to withdraw from the Straits of Magellan and it will become dry land, like those ancient passages further north mentioned by Darwin.

There are many other parts of the world where similar phenomena may be seen. The origin of the fiords in Norway has long been a matter of debate. It seems to be conceded that these inlets are made by mountains running into the sea, and more or less modified above water by ice and glaciers. They are supposed to be quite old, and certainly date back of the glacial epochs.

It may no doubt be safely assumed that these Norwegian mountains originated, like other mountains, by the uplift of faults, owing to the expulsion of lava from beneath the sea.¹ Hence the precipitous walls along the sea coast, with deep water between. The blocks

¹ Having read the earlier papers of this series with great interest, Professor Schiaparelli has kindly called my attention to the trough in the sea along the Norwegian coast. This confirmation of the theory by the illustrious astronomer of Milan is exceedingly interesting.

of the earth's crust were lifted vertically by the pushing of lava beneath them. It is in this way that all such walls of granite and other towering rock are to be explained, and the fact that the sea still encroaches on them shows how the movements came about. Probably there has been little vertical movement for a long time along the coast of Norway, and subsidence as well as elevation may have taken place, both here and elsewhere. Subsidence is common along most sea coasts, but it does not prevail in the long run, as is proved by Professor Suess's work, showing a universal lowering of the strand line throughout the world.

§ 49. *The Theory of Arches and Domes Inapplicable to the Crust of the Earth, because the Globe is not Shrinking but actually Expanding.*—In Chamberlin and Salisbury's "Geology," Vol. I, p. 583, we find the statement that

"The principle of the dome is brought into play whenever an interior shell shrinks away, or tends to shrink away, from an outer one which does not shrink. In this case there is a free outer surface and a more or less unsupported under surface towards which motion is possible. The dome may, therefore, yield by crushing or by contortion."

Owing to the important part the domed form of the crust has played in theories of deformation, these authors give quantitative results calculated by Hoskins, showing that such a dome of continental dimensions, if unsupported from below, *would sustain only 1/525th of its own weight.*

In his consideration of the "Mathematical Theories of the Earth" (*Proc. Am. Assoc. for Adv. Sci.*, 1889, p. 49), Professor R. S. Woodward reached the analogous conclusion that "If the crust of the earth were self-supporting, its crushing strength would have to be about thirty times that of the best cast steel, or five hundred to one thousand times that of granite."

In view of these results it is remarkable that any one should have viewed the earth's crust as a wholly or partially self-supporting dome; for it could not be supported even over a very small area. And moreover secular cooling is wholly inadequate to cause a separation of the interior layers from the crust. All that has been published on this point, therefore, is inapplicable to the earth, because it rests on a false hypothesis. The supposed conditions have no reality.

The earth is not shrinking and the crust does not tend to separate itself from the underlayers, except where the lava has been expelled from beneath it by earthquakes. The collapse of the crust when thus undermined, however, shows that it will not support its own weight even for a short distance. Over such small areas the crust may be taken as part of a plane, or sometimes as concave, where subsidence is already at work, and hence the theory of the arch or dome is scarcely applicable; yet the observed collapse and sinking, even where the area is no larger than in ocean troughs, confirms the above conclusions regarding the total inability of the crust to support itself.

Could therefore anything be more absurd than to discuss the stresses in the crust due to the progress of secular cooling? Stresses arise only where mountain making is in progress, and therefore chiefly near the oceans, but never appear far inland; and are wholly due to the pressure arising from steam-saturated rock and the expulsion of lava from beneath the oceans, or to movements traceable to surface water slowly sinking into the earth. The theory of arches and domes therefore confirms the present theory, but this result is indirect; and such lines of thought did not enable geologists and physicists to reach correct conceptions regarding the physics of the earth's crust.

§ 50. *On the Doctrine that Earthquake Movements depend on Slight Inequalities of Loading, and on the Abandoned Theory that the Earth is a Failing Structure.*—As the crust of the earth is made up of solid rock and soil arising from the disintegration of rock of various kinds, and as this material is elastic and yields under pressure, it naturally occurred to physicists that inequalities of surface loading deposited on adjacent areas would impose upon the underlying crust unequal stresses, and perhaps give rise to relative movements. Thus many physicists, in default of a better theory, have supposed that surface loads, depending on erosion and sedimentation, tides and varying barometric pressure, would be adequate to produce stresses that would cause readjustment of the surface strata and perhaps movements of faults in earthquakes.

It is undeniable that these varying loads do produce some small effects, and very slight changes of level may often arise in this

way. We owe the establishment of these effects of loading chiefly to the researches of Professor Sir G. H. Darwin, whose labors have so greatly advanced our knowledge of the physics of the earth. They have an extremely high importance in the theory of bodies approximating elastic solids. The undisturbed crust of the globe fulfills these conditions quite perfectly.

But to suppose that any of these small surface effects could give rise to world-shaking earthquakes which would shake down cities, raise sea coasts, and uplift mountains and islands in the sea, is too severe a test of credulity to be entertained. The class of *minute movements*, due to surface yielding under varying loads depending on sediments, tides and meteorological causes, and the class of *great movements*, due to the expulsion of lava from under the bed of the sea, are quite distinct. One class of these phenomena is micro-seismic, the other magaseismic. Previous investigators have generally confounded the two classes of phenomena, and hence they have been unable to recognize the true cause of earthquakes and mountain formation. For that reason it was necessary to restrict our investigation to the great disturbances, in the first search for the cause of the great movements of the earth's crust.

We repeat that both classes of phenomena are important in a complete theory of the physics of the earth; but the small yieldings of microscopic dimensions must be kept distinct from the great movements which have shaped the surface of the globe. Many of the small effects depend on the greater movements of the earth, while few of the great movements are influenced by surface forces—indeed none at all, except where accumulation of subterranean stresses has already rendered the conditions highly unstable. In this latter case small surface forces may occasionally accelerate the outbreak of an earthquake, just as a spark discharges a loaded gun, or a shock explodes a charge of dynamite.

On a par with the theory that slight inequalities of surface loading produce earthquakes is another equally untenable view that the earth is a failing structure. Such a doctrine might have been entertained a quarter of a century ago, when the theory of secular cooling was generally accepted, but to-day such a view is antiquated and utterly indefensible. *Owing to the demonstrated de-*

pendence of mountain making upon the sea the earth emphatically is not a failing structure. So far from failing by collapse, our planet seems to be expanding from 10 to 100 faster than it contracts from loss of heat. Thus have arisen all the highest mountains and plateaus of the globe. These great uplifts invariably face the deepest oceans, from which the expulsion of lava has mainly proceeded. Such antiquated doctrines as that the earth is a failing structure are now absolutely without excuse, and practically abandoned, and the sooner they disappear from scientific literature the better for sound knowledge of the physics of the earth.

§ 51. *Changes of the Force of Gravity in Regions Affected by the Movement of Lava Beneath the Crust.*—In view of the demonstrated movement of lava streams beneath the crust of the globe, it follows that such bodily displacement of matter but a short distance below the surface may modify sensibly the observed intensity of gravity. A region which is being undermined will have the intensity of gravity decreased, and a region which is being filled up will have the attraction increased. And not only will the *intensity* vary, but also the *direction* of the vertical, according to the movements which occur beneath the crust. And these effects may be large enough to become sensible to very refined observation.

It is in this way that the anomalies of gravity in the neighborhood of mountains have arisen in the process of mountain formation. And in regions where the expulsion of lava is still in progress, both the direction and intensity of gravity are subject to change by earthquakes. Thus in the region of the Aleutian Islands, the east coast of Japan, and many other places, such as the west coast of South America, the direction and intensity of gravity is certainly subject to change by seismic disturbances.

As the crust of the globe often suffers horizontal and vertical movement during the greatest earthquakes, the *altitude* and *azimuth* of places are also subject to change; and exact geodetic triangulation remains valid only for the interval between great earthquakes. Even then there may be a very slow and gradual settlement owing to plastic yielding of the crust and especially of the substratum beneath. Thus after earthquakes such as occur in Peru and Chili, Japan and Alaska, gravity and geodetic determinations need repeti-

tion, as was done in California after the great earthquake of April 18, 1906. And as the disturbance may alter the direction and intensity of local gravity, this possibility must be taken account of in the repetition of the observations. In order to be entirely rigorous the equations connecting the triangulation should include undetermined multipliers to take account of possible variations in the local attraction at each point. If with this general condition imposed, the triangulation before and after the earthquake comes out rigorously the same, within the limits of errors of observation, it may be supposed that the surface effects of the disturbance are insensible; otherwise the difference must be attributed to disturbances due to the earthquake.

With the refinement now possible in geodesy, it is not to be doubted that these effects will occasionally prove to be sensible to observation. The great earthquake in Assam-Bengal gave rise to horizontal movements of the order of 20 or 30 feet, which may affect the latitude by $0''.2$ or $0''.3$, and are thus within the limits of astronomical measurement. But apparent changes in latitude may result from change in the direction of gravity as well as from actual displacements of the crust, and both possibilities need to be taken into account.

§ 52. *The Necessity of Further Study of the Contours and Movements of the Sea Bottom.*—In view of the results brought out in this paper and those which have preceded it, but especially that on "The New Theory of Earthquakes and Mountain Formation as Illustrated by Processes now at Work in the Depths of the Sea," it is scarcely necessary to point out the extreme importance of further study of the contours and movements of the sea bottom. Our present maps of the ocean depths are very incomplete, although they afford a good general idea of the sea basins. But one can scarcely doubt that more exact surveys would bring to light additional mountain ranges and plateaus in regions heretofore but slightly explored; moreover certain places in the sea bottom would be found to be covered with a great variety of peaks or submerged islands which do not reach the surface.

Where the water is deep the exact survey of the bottom presents considerable difficulty. As movements arising from earth-

quakes are extremely small in comparison with the depth of the sea, it would perhaps be very difficult to detect resulting changes of the sea bottom, except in cases where sinking takes place, and the drop is large. In some cases of actual measurement in the laying of cables the sinking has been found to be hundreds of fathoms, which would be very easily recognized if the exact place of former soundings could be found. But as the changes of level in the sea bottom are fully as capricious as on land, we see that regions where mountain formation is in progress would present extreme complexity; and unless the place were very accurately known, one could not be sure that two soundings were over the same spot. This difficulty would be less near known islands than in the open sea, but it would be considerable in all places where the ship is at the mercy of the winds and currents.

Under the circumstances it is clear that great natural difficulty would arise in the exact Hydrographic survey of the deep sea, and an economic difficulty would be added, on the ground that such surveys are not required in practical navigation. Yet the laying and repair of cables would necessitate fairly accurate knowledge of the depths, and we may hope, in spite of the growth of the wireless telegraph, that our ocean surveys are still in the infancy of what they will be in another half century.

Where trenches are being dug out by earthquakes there will be the double incentive to ascertain the stage of the process and the rapidity and location of the changes. These considerations may contribute to our knowledge of particular regions; and, after all, the changes in the larger regions of the ocean bottom are small.

When the regions in which trenches are forming are once clearly recognized, attention will naturally be centered upon them, to the neglect of less disturbed areas. The most interesting regions, from a seismological point of view, are those in which islands are being uplifted and the sea bottom sinking, as near the Aleutian, Kurile and Japanese islands, the Antandes, and along the west coast of South America. But it may also be hoped that the changes in depth near individual islands, such as Guam and Martinique, will not be overlooked. Here the subsidence of the bottom often takes the form of a hole rather than of a trench. Yet

in time the movements may give rise to neighboring islands. All of these considerations show the value of accurate knowledge of the sea bottom at this epoch.

§ 53. *Greatness of the Forces which Uplift and fold the Earth's Crust.*—The tremendous power of earthquake and volcanic forces has been proverbial from the earliest ages of history, and finds expression also in the universal terror thus excited among all living beings. This extreme terror is only too well justified by the vast extent of the ruin too often wrought in different parts of the world. But probably only those who have witnessed a great earthquake can adequately appreciate the awful character of the commotion, and the gigantic forces which must underly it. This is shown also by the many published attempts to belittle the significance of earthquake disasters.

Some writers of eminent mathematical learning, but apparently lacking in grasp of the larger physical phenomena, have ascribed earthquakes to inequalities of loading, changes of barometric pressure, etc., and have with strange and almost marvelous credulity believed that the settlements of the earth thus arising would shake down cities and devastate whole countries. How these learned authorities imagined that small subsidences under the steady action of these infinitesimal forces could bring about such long continued shaking and proportionately great havoc is difficult to understand. If the forces are so small, and act so slowly, is it conceivable that the yielding could be anything else than gradual and insensible? Such minute settlements evidently would be like those now experienced in dry inland regions free from real earthquakes.

The titanic nature of the forces which have uplifted islands, mountains, plateaus and continents, can scarcely be realized; yet even the ancients grasped it to some extent when they described the whole region between Naples and Sicily as underlaid by a giant, whose movements disturbed the intervening sea bottom. In his account of the Chilean earthquake of 1835, Charles Darwin showed that the entire region from the island of San Fernandez to the Andes, about 450 miles across, had been moved together by underlying forces. "There was undoubtedly a connection between the

volcanic forces acting under this island, and under the continent, as was shown during the earthquake of 1835," says the great naturalist.

As such views have been carefully set forth by the greatest of original investigators, from Aristotle to Darwin, it is remarkable to witness the puny efforts which have been made to belittle these forces. A gentleman holding a university position, in a public address at Boston, recently likened the shock of an earthquake to the jar experienced by an insect attached to a reed which was bent till it snapped. According to this authority the earthquakes are due to the snapping of the rock of the earth's crust in the bending produced by secular cooling. Is it necessary to point out the misleading character of the comparison made, and this lecturer's utter inability to grasp the phenomena of nature?

An equally common fallacy is to ascribe these tremendous disturbances to inequalities of surface loading, due to geological and meteorological causes. Such views seem the more surprising, because formerly they have proceeded from physicists of eminent learning. But at least partial excuse may be found in the universal acceptance of the theory of secular cooling heretofore, and in the proved rigidity of the globe, which naturally led to the supposition that the crust was adjusting itself to the shrinking sphere.

Before the development of the theory of ocean leakage no adequate theory presented itself to investigators, who had unfortunately not discriminated between the great and small earthquakes. With a false premise and such an indiscriminate mixture of phenomena, real progress was difficult, if not impossible.

§ 54. *Darwin's Remarks on the Forces which Uplift Continents.*—In the extract quoted from Professor Suess, § 39, allusion has already been made to Charles Darwin's attempt to explain the origin of mountains by the direct observation of nature. His paper "On the Connection of Certain Volcanic Phenomena in South America and the Formation of Mountain Chains and Volcanoes as the Effect of the Same Power by which Continents are Elevated" (*Transactions of the Geological Society*, Vol. V, 1838, pp. 601-631) led Darwin to the conclusion:

"That the form of the fluid surface of the nucleus of the earth is subject to some change, the cause of which is entirely unknown and the effect of which is slow, intermittent, but irresistible."

Again, in the "Voyage of the Naturalist," Chapter XIV, he adds:

"The forces which slowly and by little starts uplift continents, and those which at successive periods pour forth volcanic matter from open orifices, are identical."

It is unnecessary to dwell on the irresistible power which the great naturalist correctly ascribed to volcanic and earthquake forces. It is of more interest to notice that he declared them to be identical with those which uplift continents. The same result is reached in the present paper, about three quarters of a century later, and the proof of the proposition now seems overwhelming.

If Darwin had known the cause of seismic sea waves, and had seen how trenches are dug out in the sea bottom by the expulsion of lava from beneath the sea under the land, can anyone doubt that he would have discovered and proved the leakage of the oceans, and developed the correct theory of mountain formation?

§ 55. *On the Oscillatory Movements of the Crust Shown in the Coal Measures.*—In view of the results established in this paper we need not dwell on the coal measures, and other evidences of the oscillation of the earth's crust. It suffices to say that these oscillations actually took place, as geologists have long believed. The coal fields in Pennsylvania were formed by vegetation growing rapidly and with great luxuriance over areas near the sea level which were again and again elevated and as often depressed by earthquakes. When the land was under the sea the vegetation died out, and mud and shale were deposited; when the area was again upraised another layer of vegetation was produced, and sometimes it was deposited by floods, currents, and drifting where it had not grown. This was during the Carboniferous Age, and while all the land was near the level of the ocean.

The details of such inquiries must be left to geologists and paleontologists, who study the flora and fauna of past ages. Our aim in these papers has been to give a firm basis for legitimate study and speculation, without which the phenomena of nature remain unintelligible. The progress of the sciences of the earth requires two conditions: first, true physical causes; and second, the intelligent and consistent application of these causes to the explanation

of the phenomena, both of the animate and inanimate world. The physicist must content himself with showing the mechanical causes at work and their mode of operation, while the geologist and paleontologist may deal with the evidences of life under these known conditions.

§ 56. *The Equilibrium of the Earth between the Land and Water Hemispheres Explained by the Intumescence of the Land Arising from the Expulsion of Porous Lava from under the Bed of the Sea.*

—The remarkable equilibrium preserved by the earth between the land and water hemispheres has long been a matter of speculation among philosophers. Sir John Herschel justly remarked that the high altitude of the continents in the land hemisphere would be most easily accounted for by an intumescence of the land. Pratt has since treated the question in a convincing manner, and shown that the solid parts of the earth's crust beneath the water hemisphere, with pole in New Zealand, must be denser than in the corresponding parts on the opposite side, otherwise the water would flow away towards the land hemisphere and tend to submerge it more completely. (Cf. "Figure of the Earth," 3d edition, pp. 159-160.) Hence he concludes that

"There must therefore be some excess of matter in the solid parts of the earth between the Pacific ocean, and the earth's center which retains the water in its place."

When Pratt wrote this forty years ago there was no suspicion of an intumescent layer beneath the land due to the expulsion of porous lava from beneath the bed of the sea, and accordingly he added that

"This effect may be produced in an infinite variety of ways; and therefore, without data, it is useless to speculate regarding the arrangement of matter which actually exists in the solid parts below."

Now, however, it is proved that the plateaus and continents have been uplifted by intumescent matter expelled from under the sea; and consequently we have data for speculating on how the observed effect is produced.

It is clear that all the great plateaus of the globe and even the continents themselves are underlaid by material lighter than the average of the earth's crust. Naturally the effects are greatest

where the plateaus are highest, as in Himalayas and Tibet, where the deficiency in the attraction of these elevated masses long ago attracted attention. In his "Account of the Operations of the Great Trigonometric Survey of India," Calcutta, 1879, General J. T. Walker says:

"There appears to be no escape from the conclusion that there is a more or less marked negative variation of gravity over the whole of the Indian continent, and that the magnitude of this variation is somehow connected with the height.

"Pratt's calculations had reference only to the visible mountain and oceanic masses and their attractive influences—the former positive, the latter negative—in a horizontal direction; he had no data for investigating the density of the crust of the earth below either the mountains on the one hand, or the bed of ocean on the other. The pendulum observations furnished the first direct measures of the vertical forces of gravity in different localities which were obtained, and these measures revealed two broad facts regarding the disposition of the invisible matter below; first, that the force of gravity diminishes as the mountains are approached, and is very much less on the summit of the highly elevated Himalayan table-lands than can be accounted for otherwise than by a deficiency of matter below; secondly, that it increases as the ocean is approached, and is greater on islands than can be accounted for otherwise than by an excess of matter below. Assuming gravity to be normal (in amount) on coast lines, the mean observed increase at the islands stations was such as to cause a seconds' pendulum to gain three seconds daily, and the mean observed decrease in the interior of the continent would have caused the pendulum to lose $2\frac{1}{2}$ seconds daily at stations averaging 1,200 feet above the sea level, 5 seconds at 3,800 feet, and about 22 seconds at 15,400 feet—the highest elevation reached—in excess of the normal loss of rate due to the height above the sea."

The facts here mentioned by General Walker are recognized in geodesy as applying in different degrees to all the elevated table-lands and mountainous regions of the globe. The physical cause of this deficiency in attraction is now established beyond all doubt, and the intumescence of the land, first suggested by Sir John Herschel, is shown to have arisen from the expulsion of lava from beneath the sea. Thus arises the physical condition which secures the equilibrium of the earth between the land and water hemispheres. This must be regarded as not the least remarkable among several interesting results on the physics of the earth deduced from the principle of the secular leakage of the oceans. Earthquakes, volcanoes, mountain formation, the uplift of islands, plat-



FIG. 15. Map Showing the World Ridge. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) It will be noticed that the high mountains and great plateaus everywhere face the outside, which is towards the water hemisphere. This map therefore bears impressive testimony to the truth of the New Theory, and the World Ridge stands as an everlasting witness to the secular action of the oceans in uplifting the land hemisphere of the globe.

caus, and continents, seismic sea waves, trenches and holes in the bottom of the sea, the feeble attraction of mountains, and plateaus, the equilibrium of the globe between the land and water hemispheres, are all closely related and dependent upon a single physical cause.

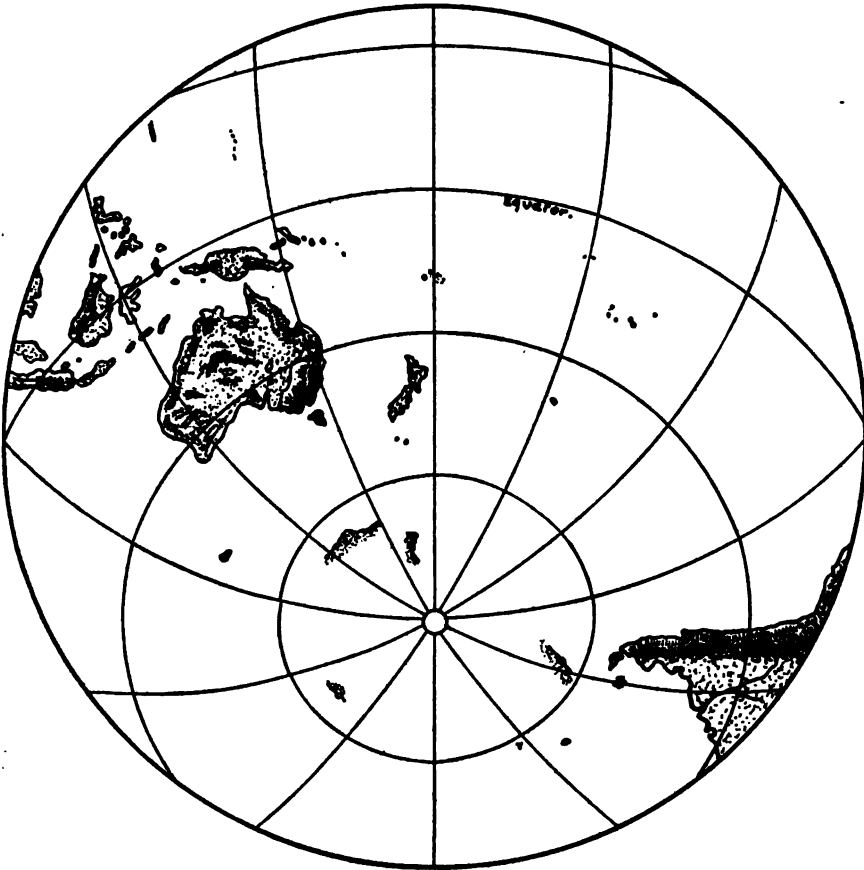


FIG. 16. Water Hemisphere, which has the World Ridge around it, drawn by W. R. Smith, of Mare Island.

In view of the order and harmony thus established among these varied phenomena, who will not concur in the view of the great Newton that "Nature is pleased with simplicity and affects not the pomp of superfluous causes"?

CONCLUSIONS.

Some of the chief conclusions reached in this and the preceding papers on the physics of the earth may be briefly summarized as follows:

1. The theory of the secular leakage of the oceans explains satisfactorily six great classes of phenomena, not heretofore closely associated, namely: (1) Earthquakes, (2) volcanoes, (3) mountain formation, (4) the formation of islands, plateaus and continents, (5) seismic sea waves, (6) the feeble attraction of mountains and plateaus long noticed in geodesy.

2. And the theory not only explains the leading facts of each class of phenomena separately, but also in relation to all the other classes of phenomena; and this harmonious mutual relationship of all the phenomena proves the theory to rest on a true physical cause.

3. A *vera causa*, once established, should not only explain all the phenomena, and all the relations, but also exclude the consideration of other possible causes, by necessary and sufficient conditions. This alone ensures the entire validity of the reasoning, and the present theory meets this severe test perfectly.

4. We have traced the details of the processes involved in mountain formation, and have exhibited illustrations of its working by processes now observed in the depths of the sea. All stages of mountain formation are thus brought out, and they are all shown to be consistent with this simple theory, which explains the principal phenomena of the earth's crust.

5. This theory explains the distribution of mountains about the continents, their great height which the contraction theory cannot account for; the formation of parallel ridges by the uplift of the side of the trough nearest the sea, when the bottom has so far subsided that the folding up of the nearer side becomes the path of least resistance in the expulsion of molten rocks from under the sea.

6. Several successive troughs are often thus dug out, with ridges forced up between them; and when the whole is raised above the water we have a series of parallel ranges, such as the Allegheny, Tuscarora and Blue Ridge Mountains in Pennsylvania and Vir-

ginia. Heretofore these vast billows of the earth's crust have been utterly bewildering to the naturalist.

7. When several such trenches have been dug out, and the expulsion of lava is from both sides, as happens when the sea is thus distributed, the ridges may finally be forced up and so crowded together from both sides that overturned dips and inverted strata are produced, as in the Swiss Alps. No previous theory has been adequate to account for this amazing phenomenon, the explanation of which is thus seen to be exceedingly simple. This test may be justly considered the *experimentum crucis* of the theories of mountain formation.

8. The Andes in South America are nothing but a vast wall or embankment erected by the Pacific Ocean, through the expulsion of lava, along its border. Hence the persistence of the earthquake belt and seismic sea waves along this coast.

9. This embankment includes not only the peaks and chains of mountains, large and small, in the Eastern and Western Cordillera, but also the intervening plateaus, such as those of Quito, Caxamarca, Cuzco, and Titicaca.

10. The molten rock expelled from under the sea is lighter than average material of the layer below the earth's crust, and when the included vapor of steam is allowed to expand, as in volcanoes, pumice is formed, and often blow out in vast quantities. Pumice of various degrees of density underlies the mountain chains, and some of it is blown out of those mountains which become volcanoes.

11. The way in which these plateaus are interwoven with the Andes mountains shows that the whole embankment is due to the continued action of one common cause. And since the mountains were uplifted by the expulsion of lava from under the sea, as proved by the uplifting of the land in earthquakes and the sinking of the sea bottom, indicated by the accompanying seismic sea waves, it follows that the plateaus also are underlaid by matter lighter than the average, which has been expelled from under the ocean.

12. The total quantity of matter thus expelled from beneath the ocean is very large, but it is the result of an infinite number of earthquakes and seismic sea waves during past geological ages. This circumstance affords us an idea of the immense age of the

Andes Mountains, which are the youngest of the great mountain systems of the globe.

13. The terrible fracturing of the crust in the sharp folding involved in the formation of the Andes enabled a vast number of volcanoes to break out, and about one hundred and five have been active within historical times.

14. The formation and activity of the volcanoes in the Aleutian and Japanese Islands is similar to those in the Andes, and represent conditions suitable to the maximum development of volcanic activity. These are sharp folds of the crust near a deep sea from which the expulsion of lava is rapid and violent.

15. The connection of earthquakes with volcanoes and of both phenomena with the sea is clearly established by the geographical distribution and by the vapor of steam emitted by volcanoes. The nature of the underlying material is shown by the ashes, cinders, pumice and lava forced out by the accumulating subterranean steam pressure.

16. Earthquakes, however, are the more general, volcanoes the more special phenomena. The mountains are formed by the sea, but only a few of the peaks break out into volcanoes. No volcano long remains active very far from the ocean or other large body of water, because as the lava hardens in the throat of the volcano the supply of steam is inadequate to maintain activity.

17. If we consider the innumerable islands in the sea, it is evident that they too have been uplifted by earthquakes. Sometimes the sea bottom near them has been undermined in the process of uplifting, and afterwards sunk down, making an adjacent hole in the bottom, and producing seismic sea waves of the first class, as in mountain formation where trenches are being dug out near the continents.

18. Seismic sea waves of the second class are produced by the uplift of the sea bottom, into ridges, or submarine plateaus and islands. In such cases the water rises suddenly without previously withdrawing from the shore.

19. But seismic sea waves of the first class due to the sinking of the sea bottom, after it is undermined by the expulsion of lava, are the most important and most celebrated. The waves at Helike,

373 B. C.; Callao, 1746; Lisbon, 1755; Arica, 1868; Iquique, 1877; Japan, 1896, were all of this class.

20. We may pass directly from the Andes to the Himalayas, and from the high plateaus of South America to those of Asia. Just as the plateaus from Quito to Titicaca were formed by the expulsion of matter from under the Pacific, so also those of Tibet and Iran are due mainly to the expulsion of lava from beneath the Indian and Pacific Oceans.

21. In the case of the plateau of Tibet the resulting uplift is partly due to the combined action of the Pacific, which thus folded the ranges to the East. With two oceans so large and deep as the Indian and Pacific coöperating in this uplift, it is no wonder that the maximum effect was produced and that Tibet became the highest plateau in the world.

22. The Himalayas are higher and further from the sea than the Andes, but the earthquake belt at the base still persists in both cases, and the configuration in regard to the sea shows that the causes at work to produce these mighty uplifts were absolutely similar. And if the mountains are due to the same cause, the plateaus are also.

23. The total height of Tibet is only about one sixth or seventh of the thickness of the earth's crust, and hence the uplift, great as it is, is not such as would necessarily produce great volcanic outbreaks at the surface.

24. Great lava flows, however, occurred in India, and some volcanic phenomenon are known in the Himalayas, but our knowledge of these mountains is not yet adequate to enable one to estimate just how much volcanic activity developed there.

25. Great lava flows are due to the rupture of the crust, by the opening of a fault near the sea, not to volcanic outbreaks. These flows are seen in Utah, Oregon and India, on a scale commensurate with the forces which have uplifted the mountains and plateaus.

26. One may pass directly from the mountains and plateaus of South America to those of Asia, and then to those on the Pacific slope of North America, by the most gradual stages.

27. In this transition the processes are so similar and the differences so small, that it is impossible to deny that the mountains

and plateaus west of the Rocky Mountains were all formed through the uplift of the land by the Pacific Ocean.

28. The North American Plateau is larger, but correspondingly lower than those in Asia, so that the volume of material involved in the two uplifts is comparable. Thus all the great plateaus of the globe are due to the action of the sea, in the course of immeasurable ages. The slowness of the process conveys the best conception of the vast interval of time since the consolidation of the globe.

29. Charles Darwin long ago held that "the forces which slowly and by little starts uplift continents and those which at successive periods pour forth volcanic matter from open orifices are identical." He showed that the southern end of South America has recently risen from the sea, and Professor Suess has shown that the universal lowering of the strand line throughout the principal countries gives a similar indication for all the lands of the globe.

30. If one end of a continent can be raised by earthquake forces depending on the sea, then obviously a whole continent can be raised by these forces; and similar uplifts can occur for all the continents in both hemispheres. The vast vertical walls of granite so often found rising from the sea in South America and elsewhere have clearly been uplifted by earthquakes.

31. We therefore reach the conclusion that the forces which have raised the mountains, islands and plateaus, have also raised the continents and established the equilibrium of the globe between the land and water hemispheres. This force is nothing else than common steam, operating through the expansion of molten rock beneath the crust and arises principally from the secular leakage of the ocean bottoms.

32. The main effect of earthquakes is the production of more land. The continents are being lifted out of the sea, in spite of erosion, as we see by the withdrawal of the oceans to a greater and greater distance from old mountain chains, such as the Rocky Mountains and Appalachians in America and the Alps in Europe.

33. But for this uplift of the land by the leakage of the oceans none of the higher forms of life could have developed upon the earth. The climate and drainage of all continents have been largely

determined by these forces, which have produced the mountains and river systems of the world.

34. We cannot prove by experiments on rock twenty miles thick that it will leak under the pressure of the ocean, but we can observe the surface movements in earthquakes such as occur in Alaska, where lava is being expelled from under the ocean and pushed under the land.

35. This movement is everywhere in the same direction, whether in Alaska, Japan, the Antandes, South America, or elsewhere—namely from the ocean towards the land. The reason of this is that much steam is formed under the oceans, but scarcely any under the land, and hence it pushes up the crust along the edge of the continents and finally almost walls them in with mountains, as was long ago pointed out by Dana.

36. The old theory of secular cooling and contraction of the globe is false and misleading, and all who have carefully examined it agree that it is totally inadequate to account for terrestrial phenomena. In fact so far from contracting it seems certain that the earth is actually undergoing a slow secular expansion.

37. The Rev. O. Fisher and Major Dutton were among the earliest to reject this theory as incapable of explaining mountain ranges. But it is remarkable that after the contraction theory was proved to be unsatisfactory, it continued to be used in all works on geology and kindred sciences, and indeed still is accepted by those who adhere to the antiquated doctrine that the earth is a failing structure. Such views had some justification a quarter of a century ago; today they are absolutely without excuse.

38. There are the best grounds for accepting the doctrine of Isostasy, as approximately true for the earth at all times; consequently there are no sensible stress-differences, or tendencies to flow, except in the layers just beneath the crust. At greater depths the matter of the earth is made solid by pressure, being at the centre about three times more rigid than nickel steel. Hence deep down the earth is now and always has been quiescent. The only layer of the earth which is plastic and perhaps viscous is that just beneath the crust; this layer flows under the tremendous forces at work in earthquake movements. It is the movement of this molten rock be-

neath the crust, chiefly when it is expelled from under the sea, which shakes down cities and devastates whole countries.

39. This expulsion of lava under the land can mean nothing else than the secular leakage of the oceans, because the mountains along the coast which are rent by the shaking of the earth till they break into volcanoes, emit chiefly vapor of steam. Moreover the unsymmetrical shape of the mountain folds, showing the gentler slope towards the shore, indicates that the folds of the crust were pushed from the direction of the sea. This was produced by the expulsion of lava under the crust arising from the secular leakage of the ocean bottom.

40. By the study of seismic and other phenomena now observed in the great laboratory of nature we may penetrate the deepest secrets hidden beneath the earth's crust, to which no mortal eye can ever bear direct witness. And these researches may greatly increase the safety of whole communities, and especially of cities and of commerce, throughout the world, by enabling us to guard against the dangers of earthquakes and seismic sea waves. This appropriate use of the laboratory of Nature is one of the ultimate objects of natural philosophy.

BLUE RIDGE ON LOUISE,
MONTGOMERY CITY, MISSOURI,
February 19, 1908.

POSTSCRIPT.

In a paper read before the Royal Society in 1902, Professor J. H. Jeans, formerly of Cambridge, now of Princeton University, has the following theory of earthquakes:

"It seems to be almost certain that the present elastic constants of the earth are such that a state of symmetrical symmetry would be one of stable equilibrium. On the other hand, if we look backward through the history of our planet, we probably come to a time when the rigidity was so much that the stable configuration of equilibriums would be unsymmetrical. At this time the earth would be pear-shaped and the transition to the present approximately spherical form would take place through a series of ruptures. It is suggested that the earth, in spite of this series of ruptures, still retains traces of a pear-shaped configuration. Such a configuration should possess a single axis of symmetry, and this, it is suggested, is an axis which meets the earth's surface somewhere in the neighbourhood of England (or possibly some hundreds of miles to the southwest of England). Starting from

England we find that England is at the centre of a hemisphere which is practically all land; this would be the blunt end of our pear. Bounding the hemisphere we have a great circle, of which England is the pole, and it is over this circle that earthquakes and volcanoes are of most frequent occurrence. Now, if we suppose our pear contracting to a spherical shape, we notice that it would probably be in the neighbourhood of its equator that the changes in curvature and the relative displacements would be greatest, and hence we would expect to find earthquakes and volcanoes in greatest number near this circle. Passing still further from England, we come to a great region of deep seas, the Pacific, South Atlantic, and Indian Oceans; these may mark the place where the 'waist' of the pear occurred. Lastly we come almost to the antipodes of England, to the Australian continent. This may mark the remains of the stalk-end of the pear." (*Nature*, Vol. LXVII., p. 190.)

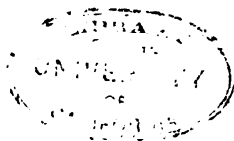
After what has been shown in this series of papers, it is unnecessary to dwell upon this hypothesis of Professor Jeans, which has the merit of originality; but we may remark that if it gave a true view of the physics of the earth, there should be a belt around the globe of at least the width of the terrestrial radius, over which the earthquakes are about equally distributed, whereas in fact they are felt principally along the margins of the Pacific Ocean. The observed earthquake belt on land is so narrow that it is clearly impossible to ascribe the effects to this supposed adjustment of the earth's figure. And of course it fails totally to account for the sinking of the sea bottom and the uplift of the coast, which is typical of mountain formation.

1908

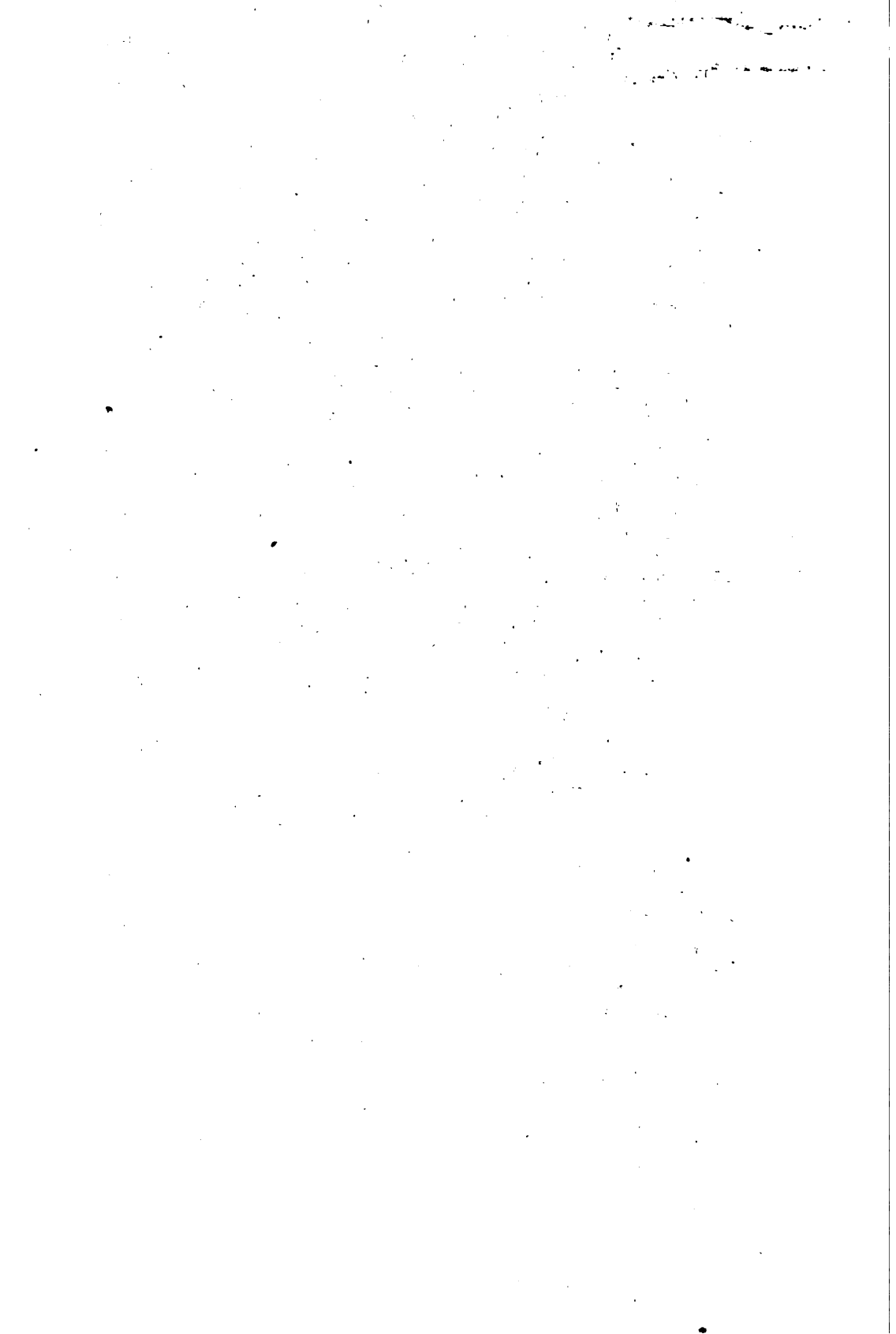
COMPLIMENTS OF THE AUTHOR.

Outline of the New Theory of Earthquakes.

T. J. J. SEE.



REPRINTED FROM POPULAR ASTRONOMY, NO. 154.



OUTLINE OF THE NEW THEORY OF EARTHQUAKES.*

T. J. J. SEE

Among all the varied natural phenomena witnessed upon our planet nothing so excites the dread and terror of mankind as an earthquake, which is at once violent and so sudden and unexpected as to alarm the calmest mind. That this direful feeling has prevailed in all ages we are amply assured by the comparisons made in the Bible and other venerable works of antiquity, which make known the consternation inspired among the people by these terrible natural commotions. Thus we read in history that some of the Emperors of Rome, especially Trajan and Hadrian, while witnessing the chariot races at Antioch and other places, found it advisable to withdraw from the amphitheatre and retire into the open spaces, in order to avoid the danger of falling walls. And the history of Greece and Rome abounds in stories of the religious anxiety excited among the people by earthquakes, which were believed to be signs of evil omen, sent from the infernal and marine divinities, but especially Poseidon, "the earthshaker," to whom so many temples were dedicated on isthmuses, promontories and other regions in the neighborhood of the sea.

When a great earthquake took place, and was followed by a series of after-shocks, impressively recalling both the terror and the disaster of the principal disturbance, which may have laid waste cities and devastated whole countries, it is not wonderful that the people who had sustained such losses were troubled and wrought up to a high pitch of excitement. In such emergencies the god Poseidon above all others called forth the veneration of the people; and he was generally held to be the most important of the infernal and marine divinities, because he held both the power of earthquakes and of those dreadful inundations by the sea, which were so often noticed

* Address delivered at the University of Missouri, May 30, 1907, being Lecture No. 2 of a general course in Natural Philosophy.

to accompany violent seismic disturbances in the Peloponnesus and elsewhere.

The wide-spread alarm and religious affliction of the inhabitants of the Peloponnesus after the great Achaian earthquake of 373 B. C. is especially remarked by Diodorus Siculus, and other historians. At the same time it is stated that the natural philosophers explain these phenomena by natural and necessary causes, rather than by the wrath of the gods. But during the ages of Greek Polytheism, and even during the earlier centuries of Christianity, such disasters were always believed by the multitude to be a sign of the divine displeasure. Sometimes they were attributed to the wickedness of an emperor, or to the sins of factional opponents; the heathens charging them upon the Christians and the Christians laying them to the idolatrous conduct of the heathens.

In view of the undeveloped state of science in former times a modern student can easily understand the great perplexity of the ancients, in the midst of such terrible calamities. The Senate of Rome on more than one occasion did what it could to alleviate the sufferings of the people, which were partly real and partly imaginary. We find several accounts of the sending of formal embassies for the offering of public sacrifices to the angry divinities. If these sacrifices did not quiet the agitating forces of nature, they at least calmed the people and thus allayed their imaginary afflictions, and were therefore of service to the state.

It is well known that both the ablest statesmen and generals of antiquity regarded earthquakes as proceeding from natural causes; and I have recently been at some pains to translate the theories held by Aristotle and other leading Greek philosophers. Aristotle gives the views of those who preceded him, and his own theory was generally adopted by his successors. We may infer this by the way in which it was followed by such writers as Strabo and Pliny.

Aristotle placed his discussion of earthquakes in the book on *Meteorology*, because he ascribed the shaking of the Earth to vapor confined within the crust, and agitating to effect an escape so as to diffuse itself in the atmosphere. He recognized the high internal temperature of the Earth from the warm springs observed to break forth in many places, and from the eruptions of volcanoes which he had witnessed in the Aeolian Islands and elsewhere. Both he and Strabo mention eruptions occurring in the bed of the sea, and they also notice the great

seismic sea waves which frequently accompany violent earthquakes originating near the sea shores.

Aristotle and Pliny distinctly remark that earthquakes are especially prevalent in maritime districts; and they attribute this phenomenon to submarine passages, conceived as deep conduits, by which air and water obtain access to the heated matter in the bowels of the Earth. They held that earthquakes are due to the agitation of imprisoned vapors even when none of it escapes to the surface, but all remains hidden beneath the Earth's crust. That the cause is the same when a volcanic outbreak occurs and when only an earthquake takes place without eruption, Aristotle affirmed on the ground of the similarity of the movement in the two cases.

To an unbiased naturalist like Aristotle it did not seem strange that in the one case the vapor should break through and diffuse itself in the atmosphere, while in the other it continued to agitate till movements occurred which gave more space beneath the Earth's crust, and was then followed by a cessation of the shocks. Aristotle's view was thus consistent with Newton's rule of philosophy, that the same effects are to be ascribed so far as possible to the same causes; and in marked contrast with the modern method of dividing earthquakes into two arbitrary classes, volcanic and tectonic, according as they are accompanied by eruption, or only by a surface's dislocation of the Earth's crust along a fault line.

While Aristotle's theory is imperfect in many respects, the general ideas underlying it are essentially sound, and in reading this work written more than twenty-two centuries ago, one cannot but be impressed both by his penetration into the nature of things, and by the vast extent of his knowledge. With characteristic independence he refused to accept the views of his predecessors, but examined *de novo* all questions upon their merits, so far as the existing state of science would permit. He is thus led to many interesting remarks, and the criticisms which he offers are often as good as can be made today.

In view of the great afflictions due to earthquakes suffered by so many countries from the earliest ages, it seems to the modern student truly remarkable that our understanding of the cause of these disturbances has remained so unsatisfactory. Whether we read in Strabo or Pliny that a great earthquake in Syria had laid waste twelve cities in a single night, or turn to the current books and press dispatches, which tell of widespread devastation by modern earthquakes, we are left

equally in the dark as to the cause of these calamities. In current discussions we often see it stated that earthquakes may occur anywhere, and that no place is free from the dreadful ravages which they inflict upon large portions of mankind. This statement obviously is not correct, yet it shows that heretofore science has not reached the true laws of these phenomena.

The main object of science is the illumination of the human mind, and much of it scarcely admits of application to practical affairs, so as to alleviate human suffering; but if we had a true science of earthquakes it ought to be indeed of the highest humane as well as scientific interest. Shall our cities continue to be devastated and rebuilt without an understanding of the disturbing cause? If so what advance has our boasted civilization made over that of the Greeks and Romans? Nay, shall we not know even the regions especially afflicted by earthquakes? We could indeed have learned this from the study of Aristotle; but in our time we claim, though not always justly, to have improved on the knowledge of the ancients. If we do not find out the regions especially subject to earthquakes, so as to forewarn the people as to what kind of houses to build, and how to protect their cities from fire in the case of an earthquake, of what practical use is science to the community? Some branches of science might be very excellent indeed and still be of no use to the multitude of people; yet this obviously is not true of a science which deals with earthquakes imperiling the lives and property of thousands of our fellow citizens.

We must confess that heretofore this knowledge of the cause of earthquakes has not been forthcoming. But as a physicist believing in the existence of natural laws, which, if known, would be of the greatest service to mankind both now and throughout coming ages, I am going to treat of earthquakes and kindred phenomenon connected with the physics of the Earth. The theory of which I shall treat has been recently presented to the American Philosophical Society in Philadelphia, and I take this occasion to acknowledge my indebtedness to this illustrious society for the publication of lengthy arguments which can be mentioned here only with the utmost brevity.*

* 1. *The Cause of Earthquakes, Mountain Formation and Kindred Phenomena connected with the Physics of the Earth.* Proc. Am. Philos. Society, 1906, issued March, 1907.

2. *On the Temperature, Secular Cooling and Contraction of the Earth*

At the time of the great earthquake at San Francisco, I had just finished the researches on the Physical Constitution of the heavenly bodies which have been recently published in the *Astronomische Nachrichten*; and as the explanations of the earthquake then made public by men of science did not seem to me to be well founded, I temporarily laid aside astronomical work in order to take up this problem of the Physics of the Earth. It is not too much to say that the papers which the American Philosophical Society did me the honor to publish have awakened a lively interest in the scientific world; and while one can scarcely hope that every difficulty has been overcome, it is evident that at least a good foundation has been laid for the true theory of earthquakes, mountain formation and kindred phenomena connected with the physics of the globe.

Since the processes involved in earthquakes are forever hidden from mortal view, the discovery of the cause involved naturally has been very difficult. But as the effects would become most sensible in earthquakes of the world-shaking class, it was felt at the outset that the investigation should be restricted to the study of these great phenomena. If the study of the greatest earthquakes enabled us to reach the underlying cause, the inquiry could later be made to include the smaller disturbances, many of which are after-shocks of the great earthquakes.

In speaking of earthquakes therefore we shall have in mind primarily earthquakes of the world-shaking class. If we had attempted to study all earthquakes together, the results could only have been hopeless confusion; for we should have been unable to discover the processes even of the greatest earthquakes.

One of the most remarkable results of these inquiries is the conclusion that the Earth is not shrinking, as commonly held in all the physical sciences for the past 80 years; but that it may indeed be slightly expanding. Another is that there is a progressive secular desiccation of the oceans, which are becoming narrower and also deeper in many places, so that as the world grows older the intensity of the earthquakes is slowly increasing, not diminishing. But obviously there has been no sensible change within the historical period.

and on the Theory of Earthquakes held by the Ancients. Proc. Am. Philos. Society, 1907.

3. The New Theory of Earthquakes and Mountain Formation as illustrated by Processes now at work in the Depths of the Sea. Proc. Am. Philos. Society, 1907, issued in March 1908.

We shall now proceed to state the cause of earthquakes and related phenomena, and after so doing shall resume the consideration of the other questions connected with the physics of the globe.

1. It is shown that the principal cause of world-shaking earthquakes is the secular leakage of the ocean bottoms, which produces steam beneath the Earth's crust. When the pressure has sufficiently accumulated the movement of the underlying molten rock shakes the Earth, lays waste cities and devastates whole countries. Much steam is formed under the ocean, but scarcely any under the land, and hence the usual process of movement consists in the expulsion of lava from beneath the sea, and the pushing of it under the land. The crust is thus pushed up and broken along the seashore, and thus forms mountains parallel to the coast.

2. The mountain systems of the world have been formed by this expulsion of lava from under the sea, and not at all by the shrinkage of the globe. Taking account of the mere lay of the mountains relatively to the sea, it is proved by the theory of probability that the chances are at least a decillion decillions to one that they were formed so exactly parallel to the coast by a true physical cause depending on the oceans. Moreover there are other phenomena to be considered of such weight that it becomes an absolute certainty that the mountains are formed by the sea.

3. The coast frequently is noticed to be upheaved during earthquakes, and the adjacent sea bottom is shown to sink, from the way in which the water retires before the inrush of the accompanying seismic sea wave. The sea does not withdraw from the land by the violence of the agitation of the ground during the earthquake, but slowly drains off afterwards, as in the ebbing of a tide, only the withdrawal is more rapid in the case of the movement before the sea wave; and as the sea level near the shore is thus lowered sometimes by forty or fifty feet, so that vessels at anchor in seven fathoms of water are left resting on the ground, it follows that the sea bottom sinks some distance from the shore, and the water rushes in from all sides to fill up the depression. When the currents meet at the center the water is forced up into a corresponding elevation, above the normal sea level, and the collapse of this aqueous ridge sends a great wave ashore, to add to the horror of the earthquake.

4. If then the sea bottom frequently sinks and the coast is

PLATE VII.



MOUNT PELÉE.

**The Burning Cloud of December 6, 1902, seen
from the sea.**



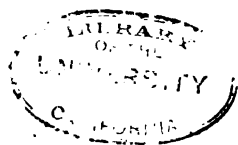
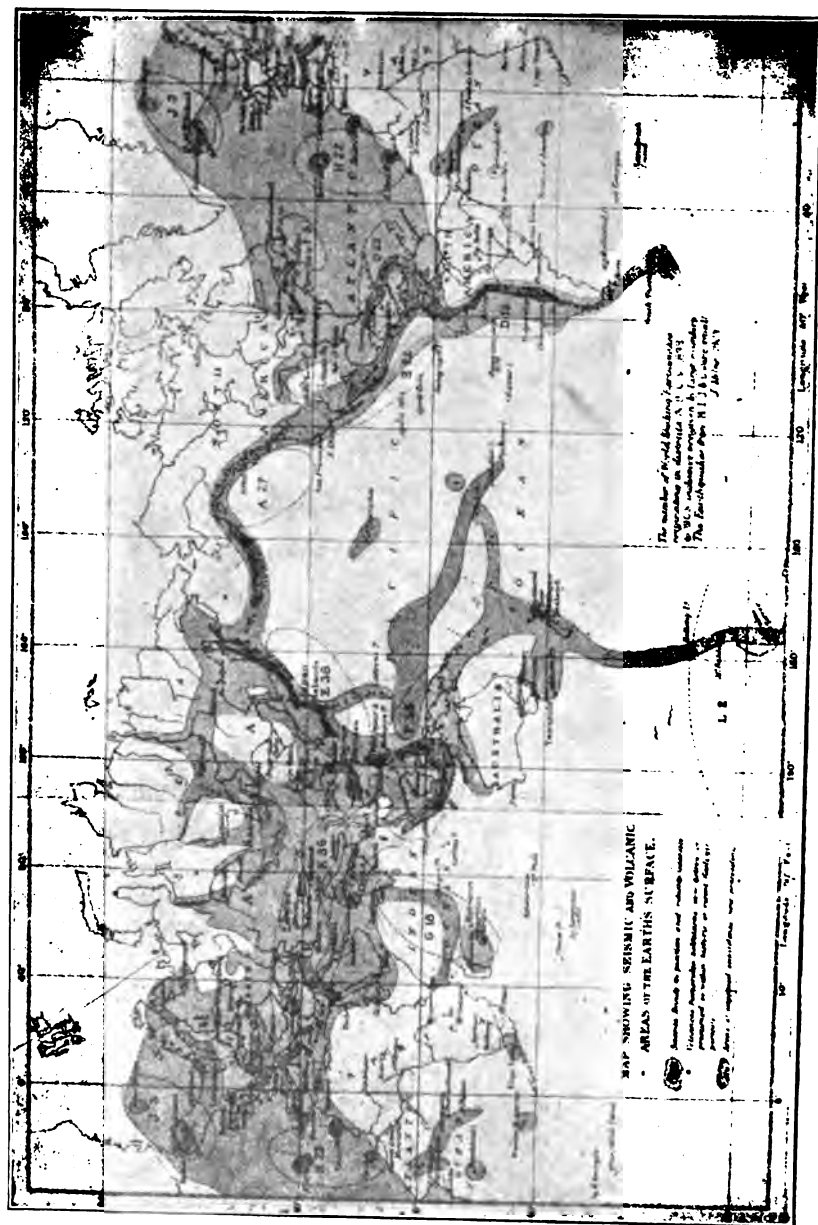


PLATE VIII.



simultaneously upraised, it follows that lava is expelled from under the sea and pushed under the land. For in the regular order of nature the sea bottom could not sink unless it was in some way undermined, and the coast could not be uplifted unless something was pushed under it, and as one sinks while the other rises it follows that lava is expelled from under the sea and pushed under the land. Not only is this process now going on along the west coast of South America, and elsewhere, as repeatedly observed within historical times, but we may also affirm that the long continuation of this undermining in the past has sunk the sea bottom down into a deep trough and at the same time pushed such vast quantities of lava under the adjacent mountains that the lofty peaks in the Andes with snow-capped summits now seem to near the stars. There is thus direct continuity between the small movements observed within the historical period and the vastly greater effect of these forces operating over immense periods of time.

5. The process by which mountains and deep ocean troughs are formed is even better illustrated in the Aleutian and Kurile Islands, where the mountains under water are just rising out of the sea and the adjacent ocean trench is very narrow, and runs exactly parallel to them for great distances (see *Manual of Tides, Coast Survey Reports, 1900, Part IV, A*, by Rollin A. Harris, including maps of the depths of the ocean). This chain is also one of the worst earthquake belts in the world, and many of the mountains have burst open and become volcanoes. The earthquakes are frequently accompanied by great seismic sea waves, showing that the bed of the ocean sinks after lava has been expelled from under it in the formation of mountains. If the process thus made out is a true law of nature it follows that all the great mountain chains of the globe were formed by this same process, though in some cases the recession of the sea coast due to the movement of the crust by earthquakes, has changed the original shapes of the troughs, and consequently can now be made out only by careful investigation.

6. Our present knowledge of the Earth's surface does not enable us to decide just what movement of the land has taken place in each case, but the parallelism of the mountains to the sea coast is sufficiently remarkable to attract universal attention. Heretofore the cause of this phenomenon has been quite obscure, and some have inferred that it is a "coincidence which is only in part causal." It is shown, however, as already

remarked, that the chances are at least a decillion decillions to one that the parallelism depends on a true physical cause connected with the sea. It is absolutely unthinkable that the Pacific ocean could be so effectively walled in by great mountain chains all around, unless the mountains were formed about the ocean itself, by the expulsion of lava, in the way we have described.

7. In 1899, September 3-20, a terrible earthquake took place at Yakutat Bay, Alaska, during which the coast was elevated for more than a hundred miles, and at the maximum the elevation amounted to $47\frac{1}{3}$ feet. Elevations of from 7 to 20 feet were common, while small depressions also occurred in a few places. This case was carefully investigated by Professor R. S. Tarr of Cornell University and Mr. Lawrence Martin of the National Geographical Society; and their memoir in the Bulletin of the Geological Society of America, Vol. 17, May, 1906, is illustrated by photographs of the most convincing kind, showing the uplifted coasts, with barnacles still adhering to the rocks. Their investigation is classic and absolutely conclusive. In the confused state of scientific opinion heretofore prevailing geologists could deny the bodily uplift of the solid land; but after the publication of this memoir they could no longer legitimately maintain this attitude. And if one instance of elevation by a powerful earthquake could be clearly established, it naturally followed that others could arise from similar causes. Last year the earthquake at Valparaiso, August 16, 1906, is said to have raised the Chilean coast about ten feet; and many similar movements at other places both in ancient and modern times can be certainly established.

8. The fact that no active volcano exists over about 100 miles from the sea or other large body of water, and the further fact that according to Geikie 999 in 1000 parts of the escaping vapor is steam, shows the dependence of volcanoes on the sea. The activity of 105 volcanoes in the Andes within historical time shows that volcanoes are nothing but ordinary mountains broken through by the pressure of subterranean steam. Hence it follows that the same forces which raise the mountain chains and peaks also cause the eruption of some of them.

9. The vapor of steam and no other is the cause of both mountain building and of volcanic outbreaks; for mountain building always takes place in or near the sea, and volcanoes

throughout the world develop near the center of the earthquake belts. Volcanoes emit chiefly vapor of steam, and eruptions generally cease when the vapor has escaped into the atmosphere. Thus earthquakes, volcanoes, mountain formation, and seismic sea waves are all due to a common cause.

10. As the expulsion of lava from under the sea causes the earthquakes and seismic sea waves, it follows also that all mountains are underlaid with pumice of various degrees of density, which is simply molten rock inflated with steam and then cooled and dried. The expulsion of such vast quantities of pumice from volcanoes shows that there must be a process for its abundant manufacture in nature, and that it must have been formed under all mountains when they were originally upheaved. The prevalence of pumice in volcanic regions is therefore accounted for in a perfectly simple manner. The grinding up of pumice makes volcanic ashes, and hence arise the vast quantities of this dust blown out of many volcanoes. Pumice and its disintegrated product in the form of ashes, result from the diminished pressure exerted on steam-saturated lava, when it is pushed under the mountains where the crust is broken, and increased expansion of the molten rock takes place.

11. The formation of islands in the sea and of plateaus on land, is to be explained by elevation of a portion of the Earth's crust by the injection of lava beneath. This lava comes from neighboring areas, which are thus undermined, unless the partial cavity is again filled up by an additional supply of molten rock. Hence plateaus such as those of Titicaca and Tibet are closely associated with the expulsion of lava, which originally caused the uplift of the Andes and Himalayas. In many cases islands in the sea have depressions near them, showing that the sea bottom was undermined in the elevation of the islands, and afterwards sank down to secure stability.

12. As all mountains and plateaus exhibit a feeble attraction when measured in geodetic operations, it follows that the cause of this phenomenon is the pumice underlying these elevated portions of the crust, which makes them attract as if they were hollow, or filled with caverns. This was noted by Bouguer and LaCandamine in their observations on Chimborazo as early as 1738.

13. When the subterranean pressure becomes great enough to shake the Earth's crust, it naturally moves at the nearest

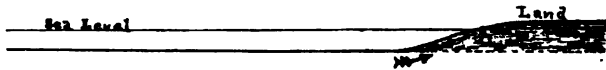
fault line, where the rocks are broken, and the resistance is least *but the movement observed is the result, not the cause of the earthquake*. It has been customary heretofore to explain earthquakes by the movement of faults, without assigning the cause of the fault movement, or by vague references to the supposed secular cooling of the Earth. Such procedure is altogether illogical, for it does not account for the origin of faults, nor even point out the correct cause of their movement.

14. If faults were due to the secular cooling of the Earth they ought to originate and move in the interior of continents as well as along the ocean shores; for acre for acre as much heat is being lost by Kansas, or Sahara, as by any sea coast or ocean bed in the world. Yet no important movements occur inland, while the sea coast is repeatedly shaken. The constant shaking of the Andes compared to the general quiescence of the Rocky mountains shows the effect of proximity to the sea, and proves that the secular cooling of the Earth is not a true cause of earthquake movements.

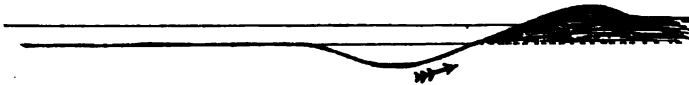
15. In the papers published by the American Philosophical Society at Philadelphia it is shown that the effects of secular cooling are wholly inappreciable, and that the Earth is not really contracting; but in all probability slightly expanding, owing to the predominant effects of elevations of the land by world-shaking earthquakes, 120,000 of which have occurred since the beginning of the Christian Era. And it is calculated that the effects of elevation may exceed the effects of contraction from 10 to 100 times, so that in all probability the globe is really expanding.

16. It turns out therefore that the doctrine of mountain formation based on the theory of contraction and now held for some 80 years is quite devoid of real foundation. If the Earth is not shrinking another cause must be sought to account for the observed elevations of the crust as seen in mountain folds; and it should explain mountain ranges in the sea as well as on the land. The present theory meets this severe test perfectly, and is beautifully illustrated by the phenomena exhibited near the Aleutian and Kurile Islands. Here the earthquakes are raising islands and at the same time sinking down the adjacent sea bottom, as may be confidently inferred from the accompanying seismic sea waves. These long narrow trenches have been dug out by the expulsion process, and it is still going on at the present time. No other interpretation of the observed phenomena is really possible.

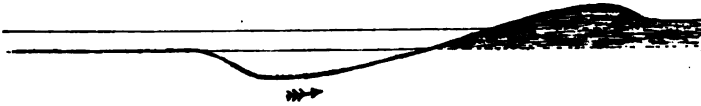
PLATE IX.



a. Mountain formation just beginning.



b. Mountain formation in the middle stages.



c. Mountain formation in the later stages.



d. New range rising from the sea.



17. The whole Plateau west of the Rocky Mountains has been raised from the sea in recent geological time. This is shown by the abundant beds of fossils, and by the numerous parallel mountain ranges nearer the Pacific Coast. The San Joaquin and Sacramento Valleys have been recently raised from the sea, and the great earthquake at San Francisco, April 18, 1906, was but one of an infinite number which have raised the coast range little by little and finally lifted California above the ocean level. Earthquakes obviously will recur in California, but no important disturbance is to be expected at San Francisco for at least a generation. This is inferred from the study of other places similarly disturbed during the historical period, and from the nature of the process of ocean leakage, which is very slow and gradual.

18. The cause of the terrible earthquakes in Japan is now perfectly clear, namely the leakage of the deep sea just to the East of Nipon, known as the Tuscarora Deep. By the expulsion of lava from under this area the whole island of Nipon has been lifted above the sea, and the process still continues with increasing violence. The east coast of Japan has risen considerably within the historical period, and naturally a movement of this kind confirms the theory here developed.

19. The present theory of mountain formation enables us to account for all the principal mountain ranges of the globe, and the more gradual slopes which they exhibit towards the sea from which the lava has been expelled in the process of elevation. In the case of islands the mountains run lengthwise, right through their centers like veritable backbones. In other cases lava escapes under larger submarine areas which will eventually be raised above the sea and formed into larger islands or continents. The principal cause of the movement of the Earth's crust is everywhere the same, but we do not yet know the details of all parts of the globe, because most of it is under water, and even that above sea level is very imperfectly surveyed.

20. As land is raised above the sea by earthquakes, it follows that the chief effect of seismic activity is the formation of more land. Since this narrows the oceans, and water is also constantly sinking down into the Earth, and only a small part of it again escapes through the vents of volcanoes, it follows that there is a secular desiccation of the oceans, but the process is excessively slow, and not certainly recognizable within the historical period. Yet a portion of the lowering

of the strand line noticed in later geological ages may be due to this cause.

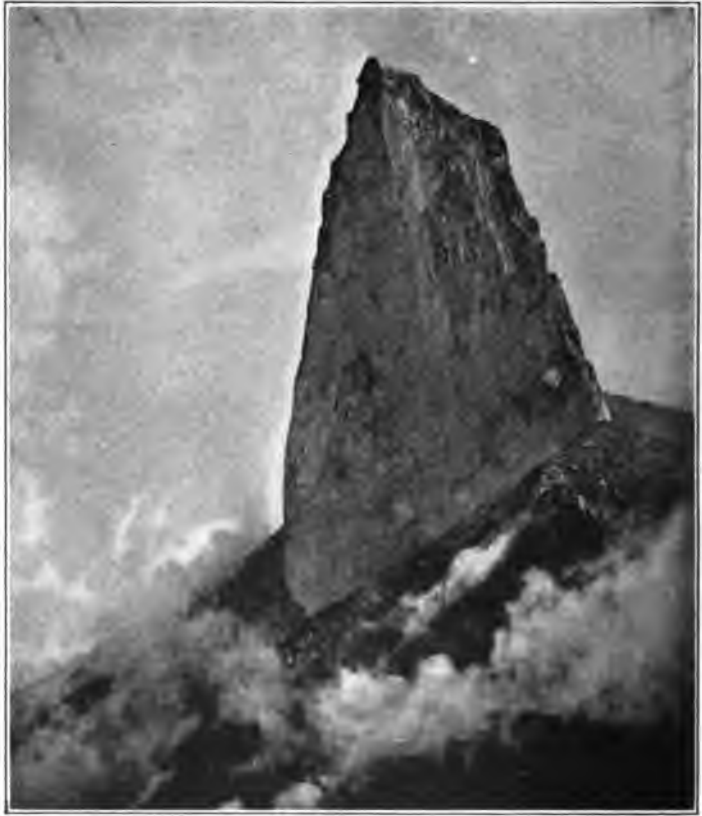
21. In studying the sinking of the sea bottoms in connection with the expulsion of lava for the elevation of coasts and the formation of mountains, the writer took up the problem of the sinking of the Homeric City of Helike, after the great earthquake in Achaia, in 373 B. C., which occurred during the lifetime of Aristotle and Plato. And it was possible to prove from historical authorities that the subsidence amounted to about 100 feet, which shows that after that earthquake had pushed lava under the mountains in Arcadia, the bed of the Gulf of Corinth gave down, and carried the shore on which Helike stood down with it, so that, as Pausanias says, only the tops of the trees about the temple of Poseidon remained above the water. This famous disaster, which happened when Plato was 54 and thus at the head of the Academy in Athens, and Aristotle was a boy eleven years old, was therefore due to the expulsion of lava from under the Gulf of Corinth. Is it not remarkable that after the lapse of so many centuries we should be able to explain by simple principles a calamity which so disturbed the Greek world, and completely bewildered even the wisest of the Athenian sages?

22. As the result of his researches Aristotle held that earthquakes are due to vapors in the Earth, seeking to escape and diffuse themselves in the atmosphere. This view was generally adopted by the ancients, for we find it clearly stated by Strabo and Pliny, who studied the writings of Aristotle. Strabo also holds the theory that the land is uplifted and depressed by earthquakes. He seems to have held that not only islands and continents but also mountains are thus produced, which essentially accords with the theory of Aristotle, who had carefully studied volcanic and earthquake phenomena, including several eruptions observed to occur in the sea. Aristotle had observed that maritime districts are especially subject to earthquakes. In view of the results of modern observations and the theory now established, may we not justly consider this to be one of the most remarkable inductions of antiquity?

23. The theory now developed was therefore vaguely outlined by the leading Greek philosophers, especially by Aristotle, who associated the causes producing earthquakes and volcanoes, islands and seismic sea waves, all of which were attributed to the accumulation of vapors in the Earth. This natural order of thought as developed by the Greeks presents a strik-



PLATE X.



THE SHATTERED OBELISK OF MOUNT PELÉE.

Photographed by Professor Angelo Heilprin.

ing contrast to the disconnected and anachronous views on these subjects still current in our own time, and admonishes us to give ample heed to the independent conceptions of the Greeks who were not so much swayed as some moderns are by contemporary opinion.

24. The theory recently current that great seismic disturbances of the Earth's crust are due to unequal loading of different areas arising in erosion, denudation and deposits of sediment is, to say the least, unworthy of modern science, because such forces could produce no uplifts whatever, nor could they produce any serious continuous shaking, even if a slight movement of the ground should occur. It is the movement of molten rock under the Earth's crust, in the process of adjustment of steam pressure, which forms mountains, shakes down cities and lays waste whole countries. The development of the highest mountain ranges about the deepest oceans shows that these great uplifts of the crust depend upon the sea and not at all on the shrinkage of the globe. The indications of nature indeed are as clear as the noon-day Sun, and all we have to do is to apply to these phenomena a little of the saving common sense which has distinguished mankind in the better ages of the human mind.

This summary of the results of these researches is necessarily incomplete, but probably sufficiently extended to afford an idea of the trend of the investigation. Among American geologists Dana approached most nearly to the true views of the physics of the Earth's crust, and we shall therefore quote his statements as they were made over forty years ago. Some of his intuitions are quite remarkable.

VIEWS OF DANA.

In the first edition of his *Manual of Geology*, 1863, J. D. Dana treats of the general Features of the Earth and shows how the continents are walled in by mountains, erected about their borders, and finally adds (p. 29):

(a) "The continents thus exemplify the law laid down, and not merely as to high borders around a depressed interior, a principle stated by many geographers,—but also as to the highest border being on the side of the greatest ocean (first announced in *American Jour. Sci.* (2) xvii, vols. iii, iv, 1847, and xxii, 335, 1856). The continents then are all built on one model, and in their structure and origin have a relation to the oceans that is of fundamental importance." He also observes that the borders of continents are from

500 to 1000 miles wide, and infers that "a continent can not be less than a thousand miles, (twice five hundred), in width," otherwise it would not have the characteristic basin form with mountain barriers about a low interior.

(b) On page 731 he discusses the evolution of the Earth's great outline reliefs, and of the successive phases in its progress, summarizing his conclusions as follows:

I. "The continents have mountains along their borders, while the interior is relatively low; and these border mountain chains often consist of two or three ranges elevated at different epochs."

II. "The highest mountain-border faces the largest ocean, and conversely."

III. "The continents have their volcanoes mainly on their borders, the interior being almost wholly without them, although they were largely covered with salt water from the Azoic age to the Tertiary. Also metamorphic rocks later than the Azoic are most prevalent near the borders."

IV. "Nearly all of the volcanoes of a continent are on the border which faces the largest ocean."

V. "The strata of the continental borders are for the most part plicated on a grand scale, while those of the interior are relatively but little disturbed."

VI. "The successive changes of level on coasts, even from the Azoic age to the Tertiary, have been in general parallel to the border mountain chains; as those of the eastern United States, parallel to the Appalachians, and those of the Pacific side, as far as now appears, parallel to the Rocky Mountains."

VIII. "The continents and oceans had their general outline or form defined in earliest time. This has been proved with regard to North America from the position and distribution of the first beds of the Lower Silurian,—those of the Potsdam epoch. The facts indicate that the continent of North America had its surface near tide-level, part above and part below it (p. 196), and this will probably be proved to be the conditions in primordial time of the other continents also. And, if the outlines of the continents were marked out, it follows that the outlines of the oceans were no less so."

The three other conclusions announced by Dana are of less interest, and need not be quoted here.

(c) The following deductions (p. 732) regarding the positions of the reliefs are of high interest:

"1. The situation of the great mountain chains, mainly near

the borders of the continents, does not indicate whether the elevating pressure acted within the continental or oceanic part of the Earth's crust. But the occurrence between the principal range and the sea coast of the larger part of the volcanoes (and, therefore, of the profound and widely-opened fractures) of these borders, of the most extensive metamorphic areas, and of the closest and most numerous plications of the strata, as so well shown in North America, are sufficient evidence that the force acted most strongly from the oceanic direction."

"2. The relation between the extent of the oceans and the height and volcanic action, etc., of their borders proves that the amount of force in action has some relation to the size and depth of the oceanic basin. The Pacific exhibits its greatness in the lofty mountains and volcanoes which begirt it."

"3. In such a movement, elevation in one part supposes necessarily subsidence in another; and, while the continental was the part of the crust which was elevated, the oceanic was the subsiding part."

In connection with the theory that the mountains are formed by the expulsion of lava from under the sea, through the operation of world-shaking earthquakes, these early views of Dana are of great interest. But in other respects he was led astray by the doctrine of the secular refrigeration of the globe; for he says that "no other cause presents itself that can comprehend in its action the whole globe and all time". He thus speaks as if the entire globe were shrinking, whereas local changes only are occurring, and these always near the sea. Dana's views that "the pressure of the subsiding oceanic portion has acted against the resisting mass of the continents; and thus the border between them has become elevated, plicated, metamorphosed and embossed with volcanoes," is alike misleading and unjustifiable. To produce such an effect the settling of the ocean basin would have to be many miles, and we have shown that no such shrinkage has taken place since the crust was formed; on the contrary there is reason to think that the Earth is expanding at a rate of from 10 to 100 times that of the contraction due to secular cooling. Moreover we have no more right to assume that the continent is squeezed by the settlement of the ocean, than that the ocean is squeezed by the settling of the continent.

(d) We have, however, recalled these views in order to do justice to the most original of the older American geologists, and also to let the student see where he departs from the true

line of thought. Many years ago Rev. O. Fisher showed that shrinkage was wholly inadequate to account for the height of the mountains observed upon the Earth, which are hundreds of times higher than the contraction theory will explain. In the paper on the cause of earthquakes it is shown that the contraction theory is also emphatically contradicted by the present distribution of mountains. And in the second paper, "On the Temperature, Secular Cooling and Contraction of the Earth, and on the Theory of Earthquakes held by the Ancients," it is shown that at present the Earth is not contracting at all; so we are compelled to abandon the older theories entirely.

As heretofore developed geology has presented the strange anomaly of offering no theories adequate to account for the uplift of mountains or the deposits of fossil beds thousands of feet above the sea. This is the more remarkable, since in the days of Humboldt, Lyell, and Darwin, the bodily elevation of the land was an accepted item of belief. But subsequently Lord Kelvin, Sir George Darwin and other eminent British physicists, showed from the investigation of tidal and other phenomena that the Earth as a whole behaved as a solid, and under the influence of this line of thought geologists gave up the doctrine of the bodily elevation of the land, and restricted themselves to the collapse of portions of the crust under gravity. Such a line of thought, however, utterly fails to explain mountains and plateaus and islands, as well as shells and other organic remains at great height above the sea level. But it was felt that the argument of the physicists against the bodily yielding of the Earth was unanswerable, and so it was, but this does not exclude the existence of a layer just beneath the crust which in earthquakes behaves as fluid.

In my researches a theory is developed by which these two views may be reconciled, and it is, I think, clearly proved that in earthquakes there is movement of molten rock beneath the crust. It is this movement of molten rock beneath the Earth's crust which produces most of the dislocations, crumpling, folding, and other phenomena studied in geology. If such a view is justifiable, it shows us how cautious we must be in drawing final conclusions, and how incomplete all the sciences still are today.

We must now refer to Daubrée's experiments, and the problem of explaining how the water gets beneath the Earth's crust, to develop the steam power operative in earthquakes. Daubrée's experiments have shown that under pressure of



PLATE XI.



its own superincumbent column water may pass through cold and enter hot rocks, by capillary action, and increase the pressure within, notwithstanding the increase of steam pressure on the under side. In this way Daubrée explained volcanic eruptions, by which a column of molten lava is forced up into the vent of a volcano. Though Daubrée's results appear to have a good experimental basis, we may prove our fundamental proposition regarding the leakage of the oceans quite independently of these experiments.

Earthquakes are the processes by which mountains are produced, and observation shows that these forces act at a depth of some fifteen miles, where the pressure is so great that no vacancies exist. When the coast is upheaved by an earthquake it is clear that no real cavity is allowed to form beneath; in the same way we may conclude that when the sea bottom sinks after an earthquake no condensation of the matter of average density takes place beneath the bed of the sea. But matter is expelled from beneath the sea bottom and pushed under the land, so that the coast is upraised and the sea bottom sinks to fill up the partial cavity formed beneath the sea by the expulsion of lava.

These phenomena are repeatedly observed in South America, the Aleutian Islands and elsewhere, and, so far as one can see admit of but one interpretation. Hence we may conclude with certainty that the Andes have been formed by the expulsion of lava from beneath the bed of the adjacent ocean; this is the true meaning of the thundering of the earthquakes under the margin of the sea already witnessed for centuries, but not heretofore understood by men of science. This subterranean thunder is the outward expression of the mighty explosive forces by which the crust along the coast is uplifted into some of the mightiest mountains of the globe.

Since the Earth is not contracting, nor experiencing any sensible changes due to secular cooling, it is evident that this expulsion of lava can only be accomplished by explosive vapor such as is seen to issue from neighboring volcanoes, which often break out into eruption simultaneously with an earthquake noticed to produce an elevation of the coast and a sinking of the sea bottom. This vapor therefore is nothing else than common steam.

Now the steam developing beneath the Earth's crust and producing earthquakes and volcanic activity can be traced to but two possible sources: First, the original magma of the

globe, which, in default of a better explanation, has been frequently invoked by the geologist; Second, the secular leakage of the ocean bottoms, effected through fifteen miles of solid rock like granite, which naturally appeals to the physicist. If the escaping steam, or any sensible part of it, came from the central magma of the globe, volcanoes and earthquakes necessarily would occur in the interior of the continents as well as along the coasts, on islands, and in the depths of the sea. For the continents are large areas, and altogether cover more than one fourth of the total surface of the globe; yet the volcanoes and world-shaking earthquakes are confined to the neighborhood of the oceans or other large bodies of water.

It clearly follows therefore that the agitating vapor does not come from the central magma of the globe, but must come from the secular leakage of the ocean bottoms. This is unmistakably indicated by the most overwhelming evidence of nature, and hence it follows that the secular leakage of the ocean bottoms through fifteen miles of rock like granite is effected by the constant pressure of the water upon the bed of the sea. When we recall that the column of water resting on the sea bottom is often five miles deep, giving a steady pressure theoretically adequate for throwing a jet to that height, it is not at all surprising that the water should work down through fifteen miles of rock like granite.

Accordingly it follows also that Daubrée's experiments are applicable to layers of rock from fifteen to twenty miles thick, and our fundamental proposition regarding the secular leakage of the ocean bottoms is proved quite independently of Daubrée's experiments.

In the case of our thinly encrusted planet so largely covered with water, the natural arrangement between the overlying oceans and the underlying molten globe constitutes a laboratory of the most imposing magnitude, infinitely transcending anything ever conceived by man, with gigantic experiments constantly going on. All that is needed therefore is for the philosopher to interpret nature's stupendous operations, which unfortunately only too often prove disastrous to human life, owing to our ignorance and disregard of natural laws. The highest duty of the philosopher is to discover these laws and make them available to the public, so as to contribute as much as possible to the safety and repose of mankind.

It is often imagined by many that the captains of industry are the principal creators of national wealth and prosperity,



and that discoveries of natural laws are of little value compared to material things. Is it necessary to point out the inadequacy of this view? Is not he who discovers how to safeguard and preserve the property of the state as essential to the public well-being as he who merely develops, without knowing how to build so as to preserve, the products of human labor? Would it be extreme to hold that a real discoverer, a true philosopher, is as valuable to the state as any Captain of industry? His worldly possessions, it is true, may be small, but his discoveries are useful to all mankind of the present and future generations; nay they are the one imperishable product of the age, a priceless heritage of civilization, and given *freely* to all the nations of the Earth!

In view of what has been proved in the researches here sketched, there will in the future be no excuse for our cities on the coasts of deep seas being consumed by conflagrations after earthquakes, for it is shown that all places on the coasts of deep seas are liable to earthquake disturbances, and the people should be prepared for such emergencies by extra and independent systems of water works. If San Francisco had possessed such knowledge before the late disaster, and had had the courage to live up to it, she would not have been laid waste by the fire, nor would the earthquake damages have proved very serious. But human frailty is such that we can learn only by experience. Let us hope that the lesson will not soon be forgotten, and that other cities on the coast will be prepared for possible emergencies.

In the same way there is little excuse for damage by seismic sea waves. If ships put promptly to sea on the first sign of the withdrawal of the water from the shore, they will usually be safe, and can ride securely over the waves due to the sinking of the sea bottom; whereas if they remain in the harbor they are almost sure to be stranded and perhaps destroyed, with enormous losses of life and property.

The researches of science therefore have an eminently practical and humane value, in addition to their purely philosophic interest. The preservation and promotion of science has therefore become one of the highest duties of the state; for the discovery of natural laws is really necessary to the protection of the people and the preservation of civilization.

Naval Observatory,
Mare Island, California,



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